MAUSAM, **58**, 2 (April 2007), 153-160

551.571.7 : 551.577.551.511 (549.3)

# Tropospheric moisture and its relation with rainfall due to nor'westers in Bangladesh

SAMARENDRA KARMAKAR and MD. MAHBUB ALAM*

*Bangladesh Meteorological Department (BMD), Dhaka - 1207, Bangladesh*

**Khulna University of Engineering & Technology, Khulna - 9203, Bangladesh*

(*Received 26 July 2004, Modified 3 July 2006*)

**e mail : malam@phy.kuet.ac.bd; malam60@hotmail.com**

**सार** – इस शोध पत्र में बंगलादेष में उत्तरी – पष्चिमी विक्षोभों के कारण होने वाली वर्षा का पूर्वानुमान लगाने के लिए क्षोभमंडल के वर्षणीय जल की मात्रा और भारित माध्य जलवाष्प का आकलन करने तथा इन प्राचलों का विभिन्न अस्थायित्व सूचकों और आगामी 24 घंटों की वर्षा, आगामी 24 घंटों की अधिकतम वर्षा एवं 24 घंटों की देष की औसत वर्षा के साथ सहसंबंध स्थापित करने का प्रयास किया गया है। यह पता चला है कि 1000 और 500 हैक्टापास्कल वायुवेग के बीच जब वर्षणीय जल की मात्रा प्रतिघंटा 25 से 45 मि. मी. तक और इसकी 35 से 45 मि. मी. तक प्रति घंटा की श्रेणी में अधिकतम आवृति 48 रही तब उत्तरी – पष्चिमी विक्षोभों की संख्या अधिकतम पाई गई। वर्षणीय जल के स्थानिक वितरण से पता चला है कि उत्तरी पष्चिमी – विक्षोभों के क्षेत्र के समीप अधिकतम वर्षणीय जल का सांद्रण हुआ है। बंगलादेष में उत्तरी – पष्चिमी विक्षोभों की तारीखों में अधिकांष अवसरों पर विषिष्ट आर्द्रता के बढने का पता चला है । जब भारित माध्य विषिष्ट आर्द्रता सतह (1000 है. पा.) और 500 है. पा. के बीच प्रति कि. ग्राम 8 से 12 ग्राम तक रही और प्रति कि. ग्राम 8 से 10 ग्राम तक की श्रेणी में अधिकतम आवृति 43 रही तब उत्तरी पष्चिमी विक्षोभों की संख्या अधिकतम पाई गई। इस अध्ययन से पता चला है कि उत्तरी पष्चिमी विक्षोभ अधिकतम भारित माध्य विषिष्ट आर्द्रता के निकट अथवा उसके पूर्वी छोर पर पाए गए है। आर्द्र और शुष्क क्षेत्रों के मिलन स्थ्ल के समीप भी उत्तरी पष्चिमी विक्षोभों का पता चला है। उत्तरी पष्चिमी विक्षोभों की तारीखों में 0000 यू. टी. सी पर ढाका में क्षोभमंडल के कुछ प्राचलों जैसे वर्षणीय जल (मि. मी. प्रति घंटा), एम. एस. डब्ल्यू. आई., एस. डब्ल्यू. आई., .एस. डब्ल्यू. आई./टी. टी., ($q_{1000}$–$q_{850}$) और भारित माध्य विषिष्ट आर्द्रता का ढाका में आगामी 24 घंटों की वर्षा, बंगलादेष में 24 घंटें की अधिकतम वर्षा और देष की औसत वर्षा के साथ सांख्यिकीय रूप से महत्वपूर्ण सहसंबंध है। सहसंबंध गुणांक अपेक्षाकृत कम हैं। सहसंबंध गुणांक अपेक्षाकृत कम है और आकलनों की मानक त्रुटियाँ अधिक हैं। आंकडों की संख्या बड़ी होने के कारण छोटे सहसंबंध गुणांक महत्वपूर्ण हैं।

**ABSTRACT.** Attempts have been made to compute the precipitable water content of the troposphere, weighted average water vapour and to correlate these parameters with different instability indices and also with the next 24-hr rainfall, next 24-hr maximum rainfall and next 24-hr country averaged rainfall in order to predicting rainfall due to nor'westers in Bangladesh. It has been found that the maximum number of nor'westers occur when the precipitable water is 25-45 mm $hr^{-1}$ between 1000 and 500 hPa, the maximum frequency being 48 in the range of 35-45 mm $hr^{-1}$. The spatial distribution of precipitable water indicates that the maximum precipitable water is concentrated over the area near the places of nor'westers. The specific humidity has been found to increase on the dates of occurrence of nor'westers in Bangladesh on most occasions. Maximum number of nor'westers occurs when the weighted average specific humidity between the surface (1000 hPa) and 500 hPa is 8-12 g $kg^{-1}$, the maximum frequency being 43 in the range of 8-10 g $kg^{-1}$. The study reveals that nor'westers have been found to occur near or at the eastern end of maximum weighted average specific humidity. It has also been found that nor'westers occur near the point of inter-section of the axes of moist and dry zones. A number of parameters of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers such as precipitable water (mm/hr), MSWI, SWI, SWI/TT, ($q_{1000}$ – $q_{850}$) weighted averaged specific humidity have statistically significant correlations with next 24-hour rainfall at Dhaka, next 24-hour maximum rainfall in Bangladesh and country averaged rainfall. The correlation co-efficients are relatively small and the standard errors of estimates are higher. The small correlation co-efficients are significant because of the large number of data.

**Key words** – Tropospheric moisture, Precipitable water, Water vapour, Nor'westers, SWEAT Index, Modified SWEAT Index, Energy Index, Total Totals Index.

## 1. Introduction

Two transition periods between southwest and northeast monsoons over the India-Bangladesh-Pakistan subcontinent are characterized by local severe storms. In Bangladesh, these transition periods are known as pre-monsoon (March-May) and post-monsoon (October-November) seasons. Of these, it is the pre-monsoon season when most of the local severe storms occur over different parts of Bangladesh with frequent intervals.

These storms are popularly known as Nor'westers or Kalbaishakhi in Bangladesh, West Bengal and Assam of India and Andhi (dust storms) in North India. Nor'wester activities in these parts of the region are directly linked up with the apparent movement of the sun towards north causing steady rise in temperature over Southern India and Bangladesh and gradually extending to the north. Such a situation becomes increasingly prominent from March and prolongs up to the end of May. Frequency of nor'westers in Bangladesh usually reaches its maximum in May, having maximum value over the Sylhet-Mymensingh-Dhaka region and is comparatively minimum over the extreme northwestern and southwestern parts of Bangladesh. There are occasions when nor'westers have been observed to occur in late February and early June. The occurrences of nor'wester in late February can be attributed to the early withdrawal of winter from Bangladesh, Assam, Bihar, West Bengal and adjoining area as well as due to the penetration of the easterly low trough to the southern tip of India and their subsequent movement towards northeast (Das *et al*., 1994), while those in early June are due to delay in the onset of southwest monsoon over this region. The delay in the occurrence of nor'westers over Bangladesh is due to presence of intense subtropical high over the Bay of Bengal. Tropospheric moisture plays an important role in the formation of nor'westers and rainfall over Bangladesh during the pre-monsoon season. The higher the depth of moisture in the troposphere, the higher the potential for the formation of nor'westers.

Nor'westers/thunderstorms bring the first rain after a long dry and hot weather during the pre-monsoon season. This rain is very important for agriculture. The knowledge of rainfall in any region is very helpful in sound cropping. In India a number of scientists made efforts to correlate summer monsoon rainfall with different meteorological parameters (Venkataraman, 1955; Kulkarni and Pant, 1969; Banerjee *et al*., 1978; Mooley and Shukla, 1989; Upadhyay *et al*., 1990). But no works have been done to predict the pre-monsoon rainfall in a country like Bangladesh.

In the present study, attempts have been made to compute the precipitable water content of the troposphere, weighted average water vapour and to correlate these parameters with different instability indices and also with the next 24-hr rainfall, next 24-hr maximum rainfall and 24-hr country averaged rainfall in order to predicting rainfall due to nor'westers in Bangladesh. The vertical distribution of water vapour ($q$), and the spatial distribution and time cross-section of the precipitable water over Bangladesh has been studied to find out the critical values for the occurrence of nor'westers. The correlation between precipitable water and the actual rainfall due to nor'westers has also been studied, which is likely to be very useful for the quantitative prediction of rainfall due to nor'westers in Bangladesh. The regression equations corresponding to the significant correlation co-efficients have been developed with the help of scattered diagram accordingly.

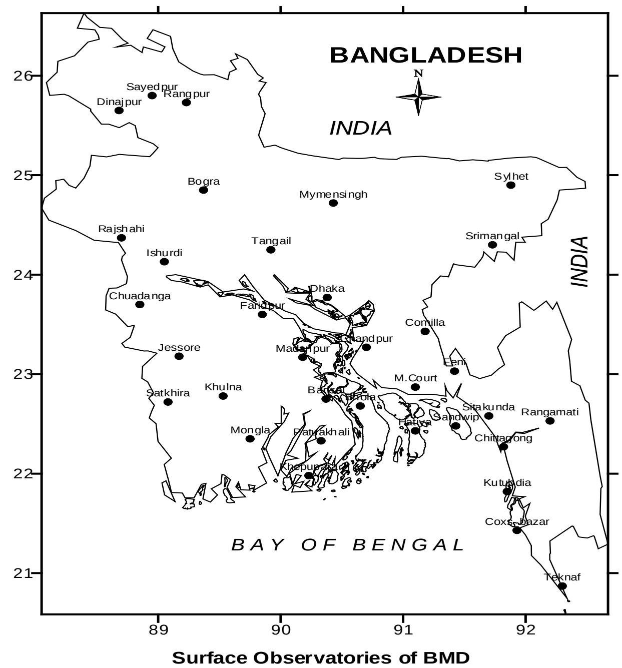


**Fig. 1.** Station location map of BMD

## 2. Data used

Twenty-four hours rainfall on the dates of occurrence of 108 nor'westers in the months of March, April and May during 1990-1995 for 34 stations in Fig. 1 have been collected from Bangladesh Meteorological Department (BMD) and utilized in the present study. Rawinsonde data of 0000 UTC at Dhaka, Chittagong and the available GTS real time data at some Indian stations on the dates of occurrence of the mentioned nor'westers have been collected from the Storm Warning Centre of BMD for the computation of specific humidity and the precipitable water of the troposphere.

## 3. Methodology

The precipitable water in the atmospheric layer, bounded by $p_1$ and $p_2$ pressure surfaces, can be expressed by (Ananthakrishnan *et al.*, 1965):

$$W = -\frac{1}{g}\int_{p_1}^{p_2} q\,\mathrm{d}p \qquad (1)$$

where g is the acceleration due to gravity and $q$ is the specific humidity at pressure level $p$.

Generally, the water vapour is mainly concentrated in the lower atmosphere up to about 500 hPa above which it has negligible contribution. For this reason, the vertically integrated magnitude of the precipitable water vapour is approximated by

$$W = -\frac{1}{g}\int_{1000}^{500} q\,dp \qquad (2)$$

To obtain *W*, one can utilize the trapezoidal rule (Haydu and Krishnamurty, 1981), which can be performed in the following manner:

$$W = \frac{1}{g}\left[ q_{1000}\int_{925}^{1000} dp + q_{850}\int_{775}^{925} dp + q_{700}\int_{600}^{775} dp + q_{500}\int_{500}^{600} dp \right]$$

$$W = \frac{75}{g}q_{1000} + \frac{150}{g}q_{850} + \frac{175}{g}q_{700} + \frac{100}{g}q_{500} \qquad (3)$$

The units used here are gmkg$^{-1}$ and gm cm$^{-2}$ for *q* and *W* respectively. The value of *W* can be converted into mm by using 1 kg m$^{-2}$ = 1 mm. (Mclntosh and Thom, 1973).

The weighted average specific humidity (WA*q*) for the standard isobaric surfaces 1000, 925, 850, 700 and 500 hPa has been computed according to the relation:

$$\text{WA}q = \frac{q_1 \times p_1 + q_2 \times p_2 + q_3 \times p_3 + q_4 \times p_4 + q_5 \times p_5}{p_1 + p_2 + p_3 + p_4 + p_5} \qquad (4)$$

where the symbols have their usual meanings. If the surface pressure is less than 1000 hPa, surface pressure is taken as $p_1$ .

Linear regression equation has been used to correlate the precipitable water, weighted average specific humidity (here in after called water vapour) with different instability indices such as Total Totals Index (TT), SWEAT Index (SWI), ratio of SWI/TT, Modified SWEAT Index (MSWI), Energy Index (EI) and Modified Energy Index (MEI) and also to correlate the same with the next 24-hr rainfall, next 24-hr maximum rainfall and 24-hr country averaged rainfall in Bangladesh. The correlation coefficients are also computed. The significant test for the correlation coefficient has been made with the help of Student's *t*-distribution (Alder and Roessler, 1964) given by

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}}$$

Where *r* is the correlation coefficient, (*n*-2) is the degree of freedom and *n* is the sample size. At 5% level (*i.e.*, 95% level of significance), if $t_{cal} > t_{0.05}$, the correlation coefficients are said to be significant.

The different stability indices and modified stability indices are given below:

Total Totals Index (TT) : $\text{TT} = T_{d850} + T_{850} - 2T_{500}$ (5)

Modified Total Totals Index (MTT) as defined by Karmakar (2005) is :

$$\text{MTT} = T_{d925} + T_{925} - 2T_{500} \qquad (6)$$

Energy Index (EI) as defined by Darkow (1968) is:

$$\text{EI} = \text{MSE}_{500} - \text{MSE}_{850} \qquad (7)$$

Modified Energy Index (MEI) as defined by Karmakar (2005) is :

$$\text{MEI} = \text{MSE}_{500} - \text{MSE}_{925} \qquad (8)$$

Severe Weather ThrEAT (SWEAT) Index (SWI) as defined by Miller (1972) is :

$$SWI = 12T_{d850} + 20(\text{TT} - 49) + 2f_8 + f_5 + 125(\text{S}_1 + 0.2) \qquad (9)$$

Modified SWEAT Index (MSWI) as defined by Karmakar (2005) is :

$$\text{MSWI} = 12T_{d925} + 20(\text{MTT} - 49) + 2f_9 + f_5 + 125(\text{S}_2 + 0.2) \qquad (10)$$

In Eqns. 9 & 10, none of the terms may be negative. Hence if $T_{d850}$, $T_{d925} < 0$, the first term of Eqns. 9 & 10 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: $\alpha_9$, $\alpha_8$ between 130° and 250°, $\alpha_5$ between 210° and 310°, $\alpha_5 - \alpha_9 > 0$, $\alpha_5 - \alpha_8 > 0$, and $f_9$, $f_8$, $f_5 \geq 15$ knots.

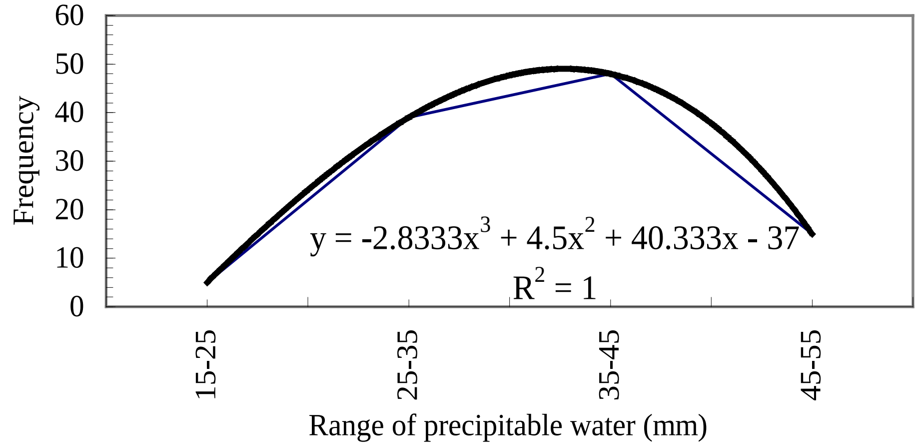


**Fig. 2.** Frequency of precipitable water content of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers in Bangladesh during 1990-1995

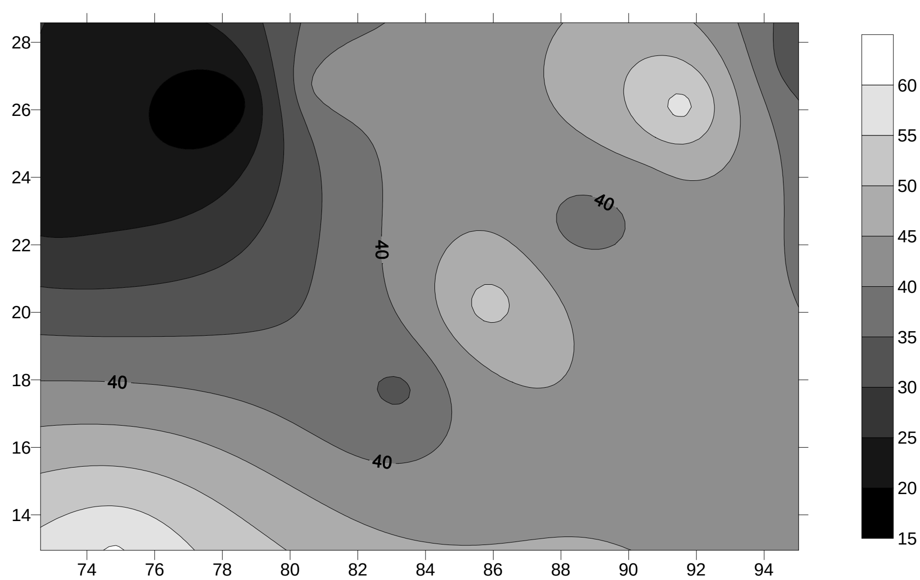


**Fig. 3.** Spatial distribution of precipitable water content of the troposphere at 0000 UTC on 14 May 1992

Where,

$T_{d925}$, $T_{d850}$ = Dew-point temperature at 925 and 850 hPa in °C

$T_{925}$, $T_{850}$, $T_{500}$ = Dry bulb temperature at 925, 850 and 500 hPa in °C.

$f_9$, $f_8$, $f_5$ = Wind speed at 925, 850 and 500 hPa in knots.

$S_1$ = Sin ($\alpha_5$ - $\alpha_8$) and

$S_2$ = Sin ($\alpha_5$ - $\alpha_9$)

$\alpha_9$, $\alpha_8$, $\alpha_5$ = Wind direction at 925, 850 and 500 hPa level

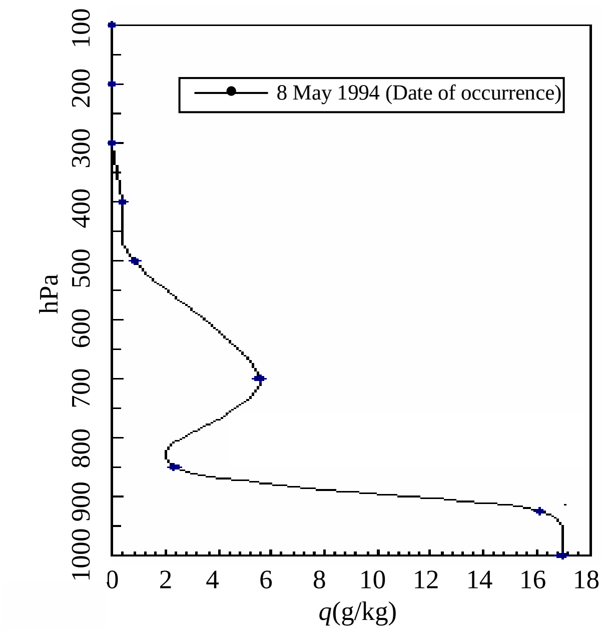


**Fig. 4.** Vertical cross-section of specific humidity on 8 May 1994 (date of occurrence of nor'westers) over Dhaka at 0000 UTC

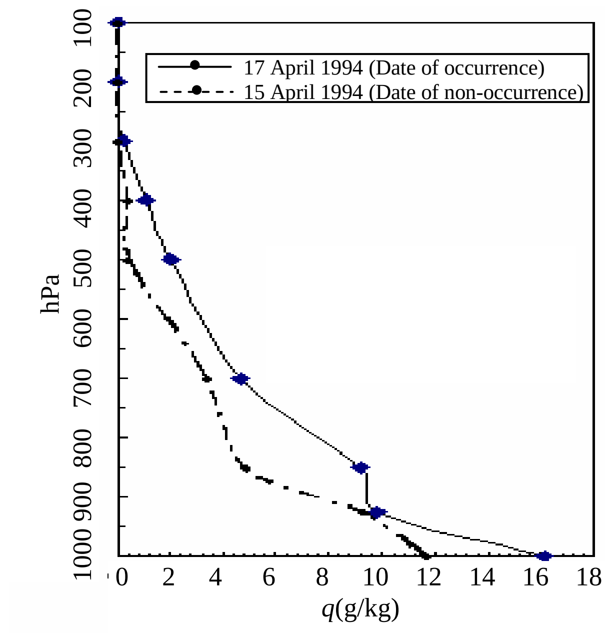


**Fig. 5.** Vertical cross-section of specific humidity on 17 April 1994 (date of occurrence of nor'westers) and 15 April 1994 (date of non-occurrence of nor'westers) over Dhaka at 0000 UTC

$MSE_{925}$, $MSE_{850}$, $MSE_{500}$ = Moist Static Energy at 925, 850 and 500 hPa level.

## 4. Results and discussion

### 4.1. *Precipitable water content of the troposphere at 0000 UTC in relation to nor'westers*

Frequency of precipitable water content of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh has been computed and the diagrams (Fig. 2) are prepared accordingly.

The frequency of precipitable water also indicates the frequency of nor'westers. It has been found that the maximum number of nor'westers occur when the precipitable water is 25-45 mm $hr^{-1}$ up to 500 hPa, the maximum frequency being 48 in the range of 35-45 mm $hr^{-1}$. Polynomial curve of third degree has been fitted to the frequency distribution. This means that the frequency of nor'wester increases cubically with the increase in precipitable water content of the troposphere. It has been also observed that favourable conditions for nor'westers to occur over Bangladesh is when the precipitable water in the atmosphere is between 15 to 55 mm. The spatial distribution of precipitable water on the dates of nor'westers has also been studied. The distribution pattern is given in Fig. 3 as an example. It has been found that the maximum precipitable water is concentrated over the area near the places of nor'westers.

### 4.2. *Specific humidity and water vapour of the troposphere at 0000 UTC in relation to nor'westers*

The specific humidity is maximum near the surface and generally decreases with height for obvious reason as can be seen from Fig. 4. It has been found that the specific humidity may be of the order of 15-20 g $kg^{-1}$ on the dates of occurrence of nor'westers. The specific humidity has been found to increase on the dates of occurrence of nor'westers in Bangladesh as can be seen from Fig. 5.

Frequency of water vapour of the troposphere over Dhaka on the dates of occurrence of nor'westers in Bangladesh has been computed and the diagrams (Fig. 6 given as an example) are prepared accordingly. The frequency of water vapour also indicates the frequency of nor'westers. It has been found that the maximum number of nor'westers occur when the water vapour between the surface and 500 hPa is 8-12 g $kg^{-1}$, the maximum frequency being 43 in the range of 8-10 g $kg^{-1}$. Polynomial curve of third degree has been fitted to the frequency distribution. This means that the frequency of nor'westers increases cubically with the increase in water vapour of the troposphere. The spatial distribution of water vapour between the surface and 500 hPa on the dates of

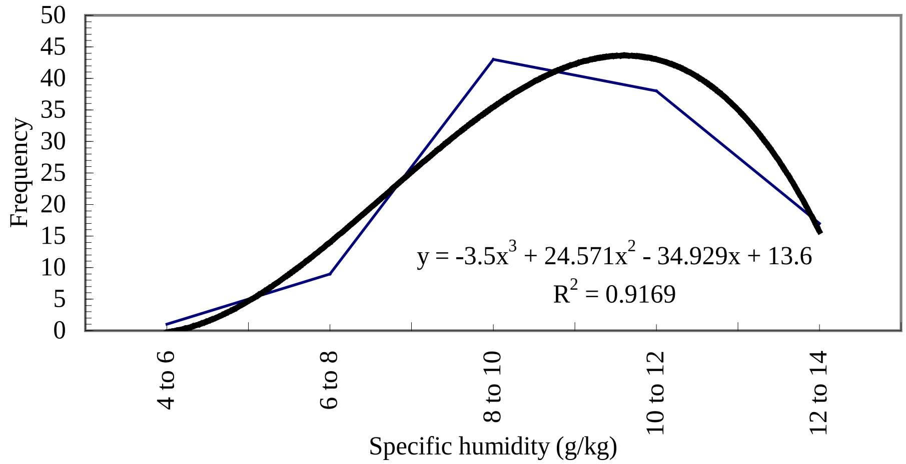


**Fig. 6.** Frequency of water vapour of the troposphere between 1000-500 hPa over Dhaka at 0000 UTC on the date of occurrence of nor'westers in Bangladesh during 1990-1995

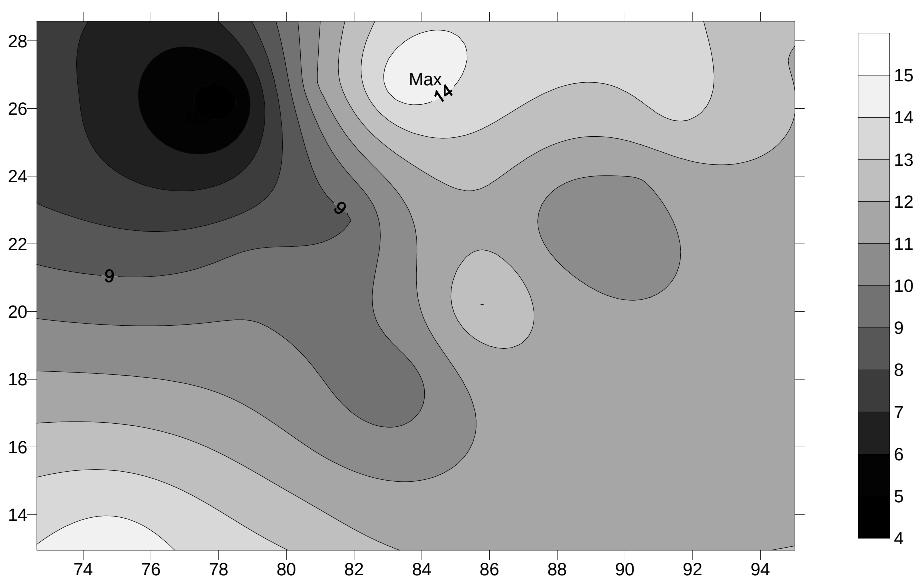


**Fig. 7.** Spatial distribution of water vapour at 0000 UTC on 14 May 1992

nor'westers has also been studied. The distribution pattern is given in Fig. 7 as an example. It has been found that nor'westers occur near or at the eastern end of maximum water vapour, the maximum water vapour being 14 g $kg^{-1}$. Nor'westers have been found to occur near the point of inter-section of the axes of moist and dry zones.

4.3. *Statistical prediction of 24-hr rainfall due to nor'westers in Bangladesh*

With a view to predicting 24-hour rainfall due to nor'westers, attempts have been made to correlate a number of parameters of the troposphere over Dhaka at 0000 UTC on the dates of occurrence of nor'westers such as precipitable water (mm/hr), MSWI, SWI, SWI/TT, difference in specific humidity at 1000 hPa and 500 hPa ($q_{1000}$-$q_{850}$), water vapour with next 24-hour rainfall at Dhaka, next 24-hour maximum rainfall in Bangladesh and country averaged rainfall.

The correlation co-efficients, regression equations corresponding to the significant correlation co-efficients and the standard error of estimates have been computed.

**TABLE 1**

**Correlation co-efficients of 24-hr rainfall with different parameters on the dates of occurrence of nor'westers**

| Correlation of | Correlation co-efficients | Standard error of estimate | Regression Equations |
|---|---|---|---|
| W at 0000 UTC *vs* CA rain | 0.24915** | ± 8.43064 | y = 0.306x - 1.3696<br>x = W, y = CA rain |
| MSWI at 0000 UTC *vs* CA rain | 0.30425** | ± 8.52495 | y = 0.0207x - 0.1335<br>x = MSWI, y = CA rain |
| W at 0000 UTC *vs* RD | 0.24660* | ± 20.22573 | y = 0.7261x - 11.136<br>x = W, y = RD |
| W at 0000 UTC *vs* $R^{max}B$ | 0.23215* | ± 35.41168 | y = 1.1923x + 13.296<br>x = W, y = $R^{max}B$ |
| LnW at 0000 UTC *vs* RD | 0.24941** | ± 20.23195 | y = 20.977x - 59.876<br>x = lnW, y = RD |
| LnW at 0000 UTC *vs* $R^{max}B$ | 0.227099* | ± 35.46158 | y = 37.199x - 76.594<br>x = lnW, y = $R^{max}B$ |
| LnW at 0000 UTC *vs* CA rain | 0.245557** | ± 8.43861 | y = 10.484x - 27.796<br>x = lnW, y = CA rain |
| SWI at 0000 UTC *vs* next RD | 0.22718* | ± 20.32454 | y = 0.0379x + 4.8865<br>x = SWEAT, y = next RD |
| SWI at 0000 UTC *vs* $R^{max}B$ | 0.29504** | ± 34.78567 | y = 0.0859x + 33.154<br>x = SWEAT, y = RB |
| MSWI at 0000 UTC *vs* $R^{max}B$ | 0.19853* | ± 35.68164 | y = 0.0566x + 29.651<br>x = MSWEAT, y = $R^{max}B$ |
| SWI/TT at 0000 UTC *vs* $R^{max}B$ | 0.25588** | ± 35.19424 | y = 3.9628x + 33.453<br>x = SWI/TT, y = $R^{max}B$ |
| $q_{1000}$-$q_{850}$ at 0000 UTC *vs* next RD | -0.212758* | ± 20.39245 | y = -1.0167x + 22.956<br>x = $q_{1000}$-$q_{850}$, y = next RD |
| $q_{1000}$-$q_{850}$ at 0000 UTC *vs* CA rain | -0.32268** | ± 8.239486 | y = -0.6432x + 14.627<br>x = $q_{1000}$-$q_{850}$, y = CA rain |
| WAq at 0000 UTC *vs* RD | 0.24844** | ± 20.2159 | y = 3.1863x - 17.265<br>x = WAq, y = RD |
| WAq at 0000 UTC *vs* RB | 0.22882* | ± 35.44041 | y = 5.1191x + 4.3875<br>x = WAq, y = $R^{max}B$ |
| WAq at 0000 UTC *vs* CA rain | 0.20912* | ± 8.51268 | y = 1.1187x - 1.6665<br>x = WAq, y = CA rain |

CA rain = next 24-hr country averaged rainfall in Bangladesh, RD = 24-hr rain at Dhaka, RB = next 24-hr rain in Bangladesh, $R^{max}B$ = next 24-hr maximum rain in Bangladesh, W = Precipitable water, * Significant at 95% level of significance, ** Significant at 99% level of significance

The results are given in Table 1. The table shows that the correlation co-efficients are relatively small but are statistically significant. The standard errors of estimates are relatively higher. The small correlation co-efficients are significant because of the large number of data (usually 106 or 108). Since the standard errors of estimates are large, the regression equations cannot be used to predict the 24-hour rainfall due to nor'westers. Therefore, it is very difficult to predict rainfall due to nor'westers statistically.

## 5. Conclusions

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

(*i*) Maximum number of nor'westers occurs when the precipitable water is 25-45 mm $hr^{-1}$ from surface to 500 hPa, the maximum frequency being 48 in the range of 35-45 mm $hr^{-1}$. It has been found that the maximum precipitable water is concentrated over the area near the places of nor'westers.

(*ii*) Maximum number of nor'westers occurs when the water vapour between the surface and 500 hPa is 8-12g $kg^{-1}$. The frequency of nor'westers increases cubically with the increase in water vapour of the troposphere.

(*iii*) Nor'westers have been found to occur near or at the eastern end of maximum water vapour, the maximum water vapour being 14 g $kg^{-1}$. Nor'westers have been found to occur near the point of inter-section of the axes of moist and dry zones.

(*iv*) On the dates of occurrence of nor'westers precipitable water (mm/hr), MSWI, SWI, SWI/TT, ($q_{1000}$-$q_{850}$), water vapour have statistically significant correlations with next 24-hour rainfall at Dhaka, next 24-hour maximum rainfall in Bangladesh and country averaged rainfall but due to large standard errors of estimates, it is difficult to predict rainfall due to nor'westers statistically.

*Acknowledgements*

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, Assistant Meteorologist, Mr. S.M. Quamrul Hassan, Assistant Meteorologist and Mrs. Masuda Mohi, Teleprinter Operator of BMD for their help in the preliminary compilation of data.

**References**

Alder, H. L. and Roessler, E. B., 1964, "Introduction to Probability and Statistics", 3rd Ed., W. H. Freeman and Company, 82-84.

Ananthakrishnan, R., Marry Selvan, M. and Chellappa, R., 1965, "Seasonal variation of precipitable water vapour in the atmosphere over India", *Indian J. Met. & Geophys*., **16**, 3, 371-384.

Banerjee, A. K., Sen, P. N. and Raman, C. R. V., 1978, "On foreshadowing southwest monsoon rainfall over India with mid-tropospheric circulation anomaly of April", *Indian J. Met. Hydrol. & Geophys*., **29**, 1&2, 425-431.

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.

Haydu, K. J. and Krishnamurty, T. N., 1981, "Moisture analysis from radiosonde and microwave spectrometer data", *J. Appl. Met*., **20**, 10, 1177-1191.

Karmakar, S., 2005, "Study of Nor'westers and development of Prediction techniques in Bangladesh during the pre-monsoon Season", Ph. D. Thesis, Khulna University of Engineering & Technology (KUET), 75-77.

Kulkarni, N. S. and Pant, M. B., 1969, "The cumulative frequency distribution of rainfall of different intensities", *Indian J. Met. & Geophys*., **30**, 2, 109-114.

Mclntosh. P. H. and Thom, A. S., 1973, "Essentials of Meteorology", Wykeham Publications (London) Ltd., 68-69.

Miller, R. C., 1972, "Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central", *Air Weather Service Tech, Rep*. 200 (Rev.), 120-190.

Mooley, D. A. and Shukla, J., 1989, "Index of activity of the monsoon trough over India", *Mausam*, **40**, 3, 247-258.

Upadhyay, D. S., Kaur, S., Misra, M. S. and Gupta, M. K., 1990, "Space correlation structure of rainfall over India", *Mausam*, **41**, 4, 523-530.

Venkataraman, K. S., 1955, "Study of Sutcliffe's theory of development in relation to rainfall in Indian area", *Indian J. Met. & Geophys*., **6**, 1, 51-56.