On the tropospheric zonal and meridional fluxes of moisture in relation to nor’westers in Bangladesh during the pre-monsoon season

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ABSTRACT. Attempts have been made to study the zonal and meridional fluxes of moisture of the troposphere prior to the occurrence of nor’westers in Bangladesh during the pre-monsoon season. The study reveals that the westerly fluxes (positive) of moisture (WFM) dominate in the troposphere over Dhaka at 0000 UTC from 925 to about 300 hPa level having maximum frequency of WFM from 61.68 to 96.26% in the layer from 925 to about 300 hPa level. The maximum WFM over Dhaka at 0000 UTC from 925 to about 300 hPa level on the dates of occurrence of nor’westers may be more than 200 gm kg^{-1} \times ms^{-1} in the lower troposphere and the maximum easterly (negative) fluxes of moisture (EFM) over Dhaka at 0000 UTC may be -128.3 gm kg^{-1} \times ms^{-1} at 1000 hPa. In the upper troposphere the zonal fluxes of moisture (ZFM) become nil in most of the cases. The vertically integrated ZFM and MFM from 1000 to 100 hPa over Dhaka at 0000 UTC on the dates of occurrence of nor’westers in Bangladesh have been computed, compared and inference has been drawn. The present study also deals with the spatial distribution of the vertically integrated ZFM and MFM from 925 to 400 hPa level over Bangladesh.
1. Introduction

Because of the peculiar geographical location of Bangladesh, a number of nor’westers affect the country every year during the pre-monsoon season and become a cause of loss of lives and properties in Bangladesh. These nor’westers are the manifestations of convective activity in the troposphere. This convective activity is a mechanism by which thermodynamic changes take place over Bangladesh and India during the pre-monsoon season. The thermodynamic changes take place due to the build up of energy, moisture, their fluxes and different dynamical parameters.

Different authors have made computation of energy, moisture and their fluxes. Palmen et al. (1958) calculated the kinetic energy released by meridional circulation between the equator and 30° N. They computed the heat transfer and the eddy moisture flow and found that the northward eddy moisture flow is $0.2 \times 10^{15}$ cal per sec. Henry and Hess (1958) developed methods for determining the contribution of each harmonic wave component to the geostrophic kinetic energy of meridional and zonal motion, and to the geostrophic fluxes of angular momentum and enthalpy. Hastenrath (1966) established the budgets of mechanical energy, latent heat, geopotential energy and sensible heat for the layers 1000-850, 850-700, 700-500 and 500-300 hPa, for both the Caribbean Sea and the Gulf of Mexico. He found that the terms of the mechanical energy are one or two orders of magnitude smaller than those of the other energy forms. According to him there is strong divergence of latent heat, concentrated in the layers 1000-850 hPa and 850-700 hPa over the Caribbean Sea during the winter half-year. Grubber (1970) studied the mean structure and energy budget over Florida Peninsula in order to assess the role played by convective processes in the vertical transfer of heat. He found the net export of energy mainly in the 300-100 hPa layer. Alestalo and Holopainen (1980) computed the horizontal fluxes of energy at European aerological stations between the surface and 150 hPa level. All these studies of energy fluxes are of different regions and not of Bangladesh-India region and the studies are not related to thunderstorms. Over the Bangladesh-India region, there are some studies related to the onset and withdrawal of southwest monsoon (Anjaneyulu, 1971; Keshavamurthy, 1968; Krishnamurthy, 1971; Chowdhury and Karmakar, 1980(a,b), 1981 and 1983; Karmakar, 1984). But no study has been made on the tropospheric fluxes of moisture related to nor’westers over this region.

This present study is an attempt to study the fluxes of moisture of the troposphere over Dhaka as well as its surrounding areas of India before the occurrence of several nor’westers in Bangladesh with a view to find out some criteria for their occurrence.

2. Data used

Real time rawinsonde data of 0000 UTC at different isobaric heights from 1000 to 100 hPa at Dhaka, Chittagong and different Indian stations have been collected from the Storm Warning Centre (SWC) of Bangladesh Meteorological Department. SWC received these data on real time basis through GTS-Link. For frequency analysis of different fluxes of moisture only the data at Dhaka has been considered and for spatial distribution all the available data of 26 stations have been considered. The stations under study are shown in Fig. 1. It may be mentioned that data of all the 26 stations were not available on the dates of occurrence of nor’westers.

In some cases, rawinsonde data were not available at one/two levels. In those cases, number of data is less than 107. The nor’westers under study occurred over different...
TABLE 1

| Pressure (hPa) | Total frequency | % Frequency of positive fluxes | % Frequency of negative fluxes | % Frequency of zero fluxes | % Frequency of positive fluxes | % Frequency of negative fluxes | % Frequency of zero fluxes |
|---------------|----------------|-------------------------------|-------------------------------|----------------------------|-------------------------------|-------------------------------|----------------------------|
| 1000          | 107            | 41.12                         | 48.60                         | 10.28                      | 92.52                         | 4.67                          | 2.80                       |
| 925           | 107            | 85.05                         | 13.08                         | 1.87                       | 98.13                         | 1.87                          | 0.00                       |
| 850           | 107            | 94.39                         | 2.80                          | 2.80                       | 71.96                         | 19.63                         | 8.41                       |
| 700           | 107            | 97.20                         | 0.00                          | 2.80                       | 24.30                         | 67.29                         | 8.41                       |
| 500           | 107            | 70.09                         | 0.00                          | 29.91                      | 19.63                         | 43.93                         | 36.45                      |
| 400           | 107            | 65.42                         | 0.93                          | 33.64                      | 28.97                         | 33.64                         | 37.38                      |
| 300           | 107            | 61.68                         | 0.93                          | 37.38                      | 34.58                         | 27.10                         | 38.32                      |
| 200           | 107            | 10.28                         | 0.00                          | 89.72                      | 6.54                          | 2.80                          | 90.65                      |
| 100           | 107            | 0.00                          | 0.00                          | 100.00                     | 0.00                          | 0.00                          | 100.00                     |

parts of Bangladesh during the pre-monsoon season of 1990-1995. For spatial distribution of the instability indices, 26 cases of nor’westers have been considered for the study. Rawinsonde data at Dhaka on the dates of non-occurrence of nor’westers (especially 1 day before the date of occurrence of nor’westers) have also been collected from Bangladesh Meteorological Department for the comparative study.

3. Methodology

3.1. Water vapour fluxes in the atmosphere

For a given level in the atmosphere, the magnitude of the instantaneous zonal and meridional fluxes of water vapour are given by:

\[ Q_{\lambda} = qu \]  
\[ Q_{\phi} = qv \]  

Where

\[ Q_{\lambda}, Q_{\phi} = \text{Zonal and meridional water vapour flux for a given level (gm kg}^{-1} \times \text{ms}^{-1}) \]

\[ q = \text{Specific humidity (gm kg}^{-1}) \]

\[ u, v = \text{Zonal and meridional wind component (ms}^{-1}) \]

3.2. Vertically integrated fluxes of moisture

The vertically integrated zonal and meridional components of the moisture flux are given by

\[ Q_{\lambda} = g^{-1} \int_{500}^{1000} qudp \]

\[ Q_{\phi} = g^{-1} \int_{500}^{1000} qvpd \]

The integration has been done by taking the layer mean values of the fluxes of moisture from 1000 to 400 hPa level over Dhaka and for spatial distribution from 925 to 100 hPa level. Here 925 hPa has been taken because the surface pressure becomes less than 1000 hPa level in most of the stations during the pre-monsoon season. The unit of \( Q_{\lambda} \) and \( Q_{\phi} \) is kg x ms\(^{-1}\).

4. Results and discussion

The zonal fluxes of moisture (ZFM) and meridional fluxes of moisture (MFM) over Dhaka at 0000 UTC have been computed at different isobaric levels on the dates of occurrence of about 107 nor’westers over Bangladesh during pre-monsoon season of 1990-1995. The fluxes over Dhaka have also been computed for the dates of non-occurrence of nor’westers. A comparative study of the frequency of westerly (positive) and easterly (negative) and southerly (positive) and northerly (negative) fluxes of moisture have been made and are given in Table 1.
Fig. 2. Vertical variation of the maximum and minimum zonal fluxes of moisture (g kg\(^{-1}\) × ms\(^{-1}\)) over Dhaka at 0000 UTC on the dates of occurrence of nor’westers over Bangladesh.

Fig. 3. Vertical profiles of the zonal fluxes of moisture (g kg\(^{-1}\) × ms\(^{-1}\)) over Dhaka at 0000 UTC on the date of occurrence (10 March 1990) and the date of non-occurrence (9 March 1990).

Fig. 4. Vertical variation of the maximum and minimum meridional fluxes of moisture (g kg\(^{-1}\) × ms\(^{-1}\)) over Dhaka at 0000 UTC on the date of occurrence of nor’westers over Bangladesh.

Fig. 5. Vertical profiles of the meridional fluxes of moisture (g kg\(^{-1}\) × ms\(^{-1}\)) over Dhaka at 0000 UTC on the date of occurrence (29 April 1990) and the date of non-occurrence (28 April 1990).
4.1. Zonal fluxes of moisture (ZFM) over Dhaka

Table 1 shows that the EFM dominates at 1000 hPa in many cases over Dhaka on the dates of occurrence of nor’westers over Bangladesh and the EFM decrease with height. The WFM dominate in the troposphere from 925 to 300 hPa level having maximum frequency of WFM from 61.68 to 97.20% in the layer from 925 to about 300 hPa level. In the upper troposphere the ZFM become nil in most of the cases.

The maximum WFM over Dhaka at 0000 UTC on the dates of occurrence of nor’westers may be 223.6, 203.8, 315.6, 174.1, 88.2, 38.7 and 19.1 gm kg\(^{-1}\) × ms\(^{-1}\) at 1000, 925, 850, 700, 500, 400 and 300 hPa levels respectively and then the fluxes become unimportant above. The maximum EFM over Dhaka at 0000 UTC may be -128.3, -59.7, -12.6 and -50.2 gm kg\(^{-1}\) × ms\(^{-1}\) at 1000, 925, 850 and 700 hPa levels respectively and then the fluxes become unimportant above. The maximum ZFM are always westerly on the dates of occurrence of nor’westers.

The vertical profiles of the ZFM over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor’westers in Bangladesh are studied and the variation is shown in Fig. 3 as an example. It has been found that the fluxes are mainly westerly and more westerly in the lower and middle troposphere on the dates of occurrence of nor’westers as compared to the fluxes on the dates of non-occurrence. The fluxes become nil in the upper troposphere.

4.2. Meridional fluxes of moisture (MFM) over Dhaka

Table 1 shows that the southerly flux of moisture (SFM) dominate from 1000 to about 300 hPa level in most of the cases over Dhaka on the dates of occurrence of nor’westers over Bangladesh, having maximum frequency of SFM in the lower troposphere and the frequency of SFM decreases with height. The frequency of SFM is 92.52% at 1000 and 98.13% at 925 hPa levels. The frequency of northerly flux of moisture (NFM) is less in the lower troposphere having maximum frequency of NFM from 67.29 to 27.10% in the layer from 700 to about 300 hPa level. In the upper troposphere the MFM become nil in most of the cases.

The maximum SFM over Dhaka at 0000 UTC on the dates of occurrence of nor’westers may be 199.4, 250.2, 196.9, 74.9, 23.6, 21.6 and 12.3 gm kg\(^{-1}\) × ms\(^{-1}\) at 1000, 925, 850, 700, 500, 400 and 300 hPa levels respectively and then the fluxes become unimportant above. The maximum NFM over Dhaka at 0000 UTC may be -109.1, -163.5, -174.1, -74.4 and -31.0 gm kg\(^{-1}\) × ms\(^{-1}\) at 1000, 925, 850, 700 and 500 hPa levels respectively and then the fluxes become unimportant above on the dates of occurrence of nor’westers in Bangladesh. Fig. 4 shows, as an example, the variation of maximum and minimum ZFM with height. The maximum MFM are always southerly on the dates of occurrence of nor’westers.

The vertical profiles of the MFM over Dhaka at 0000 UTC on the dates of occurrence and non-occurrence of nor’westers in Bangladesh are studied and the variation is
shown in Fig. 5 as an example. It has been found that the fluxes are mainly southerly and more southerly in the lower and middle troposphere on the dates of occurrence of nor'westers as compared to the fluxes on the dates of non-occurrence. The fluxes become nil in the upper troposphere.

4.3. Vertically integrated zonal and meridional fluxes of moisture over Dhaka

The ZFM and MFM computed at different isobaric levels over Dhaka at 0000 UTC on the dates of occurrence of nor’westers, have been integrated from 1000 to 400 hPa level by taking the layer mean moisture flux. The vertically integrated ZFM and MFM for 107 nor’westers are shown in Fig. 6. Fig. 6 shows that the vertically integrated ZFM are much higher than that of the MFM.

The frequency of vertically integrated ZFM and MFM over Dhaka at 0000 UTC on the dates of occurrence of nor’westers in Bangladesh is given in Table 2. The table shows that only 3 nor’westers out of 106 (2.83%) the fluxes are easterly and the fluxes are westerly in 97.17% cases. About 83.96% WFM are in the range of \((10-40) \times 10^5 \text{ kg} \times \text{ms}^{-1}\) and 7.55% WFM are in the range of \((40-60) \times 10^5 \text{ kg} \times \text{ms}^{-1}\) on the dates of occurrence of nor’westers in Bangladesh. The vertically integrated MFM are northerly in 19.63% cases of nor’westers. The MFM are southerly in 80.37% cases and about 39.25% MFM are in the range of \((10-30) \times 10^5 \text{ kg} \times \text{ms}^{-1}\) and 4.67% SFM are in the range of \((30-50) \times 10^5 \text{ kg} \times \text{ms}^{-1}\).

The vertically integrated ZFM may vary from \(-4.84 \times 10^5\) to \(93.78 \times 10^5 \text{ kg} \times \text{ms}^{-1}\) and the vertically integrated MFM may vary from \(-17.63 \times 10^5\) to \(40.85 \times 10^5 \text{ kg} \times \text{ms}^{-1}\) over Dhaka at 0000 UTC on the dates of occurrence of nor’westers in Bangladesh.

4.4. Spatial distribution of the vertically integrated ZFM and MFM

The spatial distribution of the vertically integrated ZFM from 925 to 400 hPa level over Bangladesh and its surrounding areas has been analyzed for several cases of nor’westers and one distribution is shown in Fig. 7(a) as an example. It has been found that vertically integrated

Figs. 7(a&b). Spatial distribution of vertically integrated zonal and meridional fluxes of moisture at 0000 UTC on 14 May 1992 (date of occurrence) from 925 to 400 hPa \((\times 10^5 \text{ kg} \times \text{ms})\)
TABLE 2

Frequency of vertically integrated zonal and meridional fluxes of moisture over Dhaka at 0000 UTC on the dates of occurrence of nor’westers in Bangladesh

| Range of fluxes (×10^5 kg × ms^-1) | Frequency of vertically integrated zonal fluxes of moisture | Frequency of vertically integrated meridional fluxes of moisture |
|-----------------------------------|-----------------------------------------------------------|---------------------------------------------------------------|
| -20 to –10                        | 0                                                         | 2                                                             |
| -10 to 0                          | 3                                                         | 19                                                            |
| 0 to 10                           | 6                                                         | 39                                                            |
| 10 to 20                          | 39                                                       | 29                                                            |
| 20 to 30                          | 35                                                       | 13                                                            |
| 30 to 40                          | 16                                                       | 4                                                             |
| 40 to 50                          | 5                                                        | 1                                                             |
| 50 to 60                          | 3                                                        | 0                                                             |
| Total                             | 107                                                      | 107                                                           |

WFM dominate over Bangladesh on most of the dates of occurrence of nor’westers and the gradient of fluxes is steep over the country. The range of the vertically integrated ZFM for the layer is about (2-12) × 10^5 kg × ms^-1 over Bangladesh in most of the cases. A trough of WFM exists over Bihar, sub-Himalayan West Bengal and north-western Bangladesh extending to south-eastern Bangladesh as can be seen from Fig. 7(a).

The spatial distribution of the vertically integrated MFM from 925 to 400 hPa level over Bangladesh and its surrounding areas has been analyzed for several cases of nor’westers and one distribution is shown in Fig. 7(b) as an example. It has been found that vertically integrated SFM dominate over south-southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor’westers and the gradient of fluxes is steep over the region. There exist NFM in the northwestern and northeastern parts of the country in many cases. The range of the vertically integrated MFM for the layer is about (3-14) × 10^5 kg × ms^-1 in most of the cases. A trough of WFM exists over Bihar, sub-Himalayan West Bengal and north-western Bangladesh extending to south-eastern Bangladesh as can be seen from Fig. 7(b).

5. Conclusions

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

(i) The westerly fluxes (positive) of moisture dominate in the troposphere over Dhaka at 0000 UTC from 925 to 200 hPa level having maximum frequency of westerly fluxes from 61.68 to 96.26% in the layer from 925 to about 300 hPa level. In the upper troposphere the zonal fluxes of moisture become nil in most of the cases.

(ii) The maximum westerly fluxes of moisture over Dhaka at 0000 UTC on the dates of occurrence of nor’westers may be more than 200 gm kg^-1 × ms^-1 in the lower troposphere and the maximum easterly fluxes of moisture may be -128.3 gm kg^-1 × ms^-1 at 1000 hPa.

(iii) The zonal fluxes of moisture over Dhaka at 0000 UTC are mainly westerly and more westerly in the lower and middle troposphere on the dates of occurrence of nor’westers as compared to the fluxes on the dates of non-occurrence.

(iv) The southerly fluxes (positive) of moisture dominate in the troposphere over Dhaka at 0000 UTC from 1000 to 300 hPa level. The frequency of southerly is 92.52% at 1000 hPa and 98.13% at 925 hPa level. The frequency of northerly fluxes of moisture is less in the lower troposphere having maximum frequency of northerly fluxes from 67.29 to 27.10% in the layer from 700 to about 300 hPa level. In the upper troposphere the meridional fluxes of moisture become nil in most of the cases.

(v) The meridional fluxes of moisture are mainly southerly and more southerly in the lower and middle troposphere on the dates of occurrence of nor’westers as compared to the dates of non-occurrence.
The frequency of vertically integrated fluxes of moisture over Dhaka at 0000 UTC from 1000 to 100 hPa on the dates of occurrence of nor’westers in Bangladesh are westerly in 97.17% cases and southerly in 80.37% cases. There exist vertically integrated northerly fluxes in the northwestern and northeastern parts of the country in many cases. The range of the vertically integrated meridional fluxes of moisture at 0000 UTC for the layer is about \( (3-14) \times 10^5 \text{ kg} \times \text{ms}^{-1} \) in most of the cases.

The spatial distribution of the vertically integrated ZFM from 925 to 400 hPa level over Bangladesh and its surrounding areas at 0000 UTC indicates that vertically integrated WFM dominate over Bangladesh and/or eastern Uttar Pradesh, Bihar and Sub-Himalayan West Bengal of India on the dates of occurrence of nor’westers and the gradient of fluxes is steep over the country. The vertically integrated southerly fluxes of moisture dominate over south southwestern and adjoining central parts of Bangladesh on the dates of occurrence of nor’westers and the gradient of fluxes is steep over the region.

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