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Vertically-integrated tropospheric moisture, energy and their fluxes over Bangladesh during landfall of tropical cyclones

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सार — कुछ समय पहले बंग्लादेश के तट पर आए तीन बड़े चक्रवातों द्वारा धरातल को प्रभावित करने के दौरान, बंग्लादेश में ऊर्ध्वाधर समाकलित क्षोभ-मंडलीय नमी, ऊर्जा तथा इनकी कमी और अधिकता के कारण इनमें आने वाले परिवर्तनों का अध्ययन किया गया है। इसका पता चला है कि बंगाल की खाड़ी में चक्रवातों के बनने की अवस्थाओं के दौरान देश की ऊर्ध्वाधर समाकलित क्षोभमंडलीय नमी, शुष्क स्थिर ऊर्जा, गुप्त ऊर्जा तथा कुल ऊर्जा में कमी की प्रवृत्ति होती है, तथा जब चक्रवात उत्तर दिशा की ओर बढ़ता हुआ अंततः धरातल को प्रभावित करता है तब इनमें उल्लेखनीय वृद्धि की प्रवृत्ति पाई जाती है।

चक्रवात के उत्तर दिशा की ओर बढ़ने के दौरान नमी के जोनल तथा उत्तर दक्षिणी समाकलित परिसंचरण, शुष्क स्थिर ऊर्जा, गुप्त ऊर्जा तथा कुल ऊर्जा के परिमाण तथा संकेत दोनों में महत्वपूर्ण परिवर्तनों का पता चला है।

ABSTRACT. The changes in the vertically-integrated tropospheric moisture, energy and their fluxes over Bangladesh have been studied during the landfall of three major cyclones at Bangladesh coast in the recent past. It has been found that the vertically- integrated tropospheric moisture, dry static energy, latent energy and total energy over the country have a tendency to decrease at the formation stages of the cyclones in the Bay of Bengal and then the same shows significant increase as the cyclones move northwards for ultimate landfall.

The integrated zonal and meridional fluxes of moisture, dry static energy, latent energy and total energy exhibit significant changes both in magnitudes and signs during the northward movement of the cyclones.

Key words — Tropical cyclone, Moisture, Dry static energy, Latent energy, Total energy, Zonal fluxes and Meridional fluxes.

1. Introduction

Moisture, energy and their fluxes in the atmosphere play very important role in maintaining general and regional circulations. The reality has, therefore, drawn much attention of the scientists in the evaluation of tropospheric moisture, energy and their fluxes during the past few decades. For example, the work of Ananthakrishnan *et al.* (1965), Newell *et al.* (1972, 1974), Chowdhury and Karmakar (1983) may be cited. Fisher (1958) studied the exchange of energy between the sea and the atmosphere in relation to hurricane behaviour. He concluded that the hurricane responds to the eddy energy flux in a logical manner, *i.e.*, where the fluxes are weak, the storms weaken and where the fluxes seem to be strongest, the storms strengthen. Riehl and Malkus (1958) studied the heat balance in the equatorial trough zone. According to them, the equatorial trough zone receives the latent heat accumulated by the lower trades, lifts and converts energy, balancing radiation losses and exports the residue aloft in the form of sensible heat and potential energy. Gangopadhyaya and Riehl (1959) studied the exchange of heat, moisture and momentum between hurricane Ella (1958) and its environment.

Comparatively little is known about the moisture, energetics and their fluxes over India-Bangladesh-Pakistan sub-continent, especially with respect to the tropical cyclones of the Bay of Bengal making landfall either at Bangladesh coast or Indian coast except the study made by Anjaneyulu *et al.* (1965) in which the latent heat and sensible heat energy have been estimated around the lateral boundary of October 1963 cyclone. They also computed the heat and moisture fluxes. In the present paper, vertically- integrated tropospheric moisture, energy and

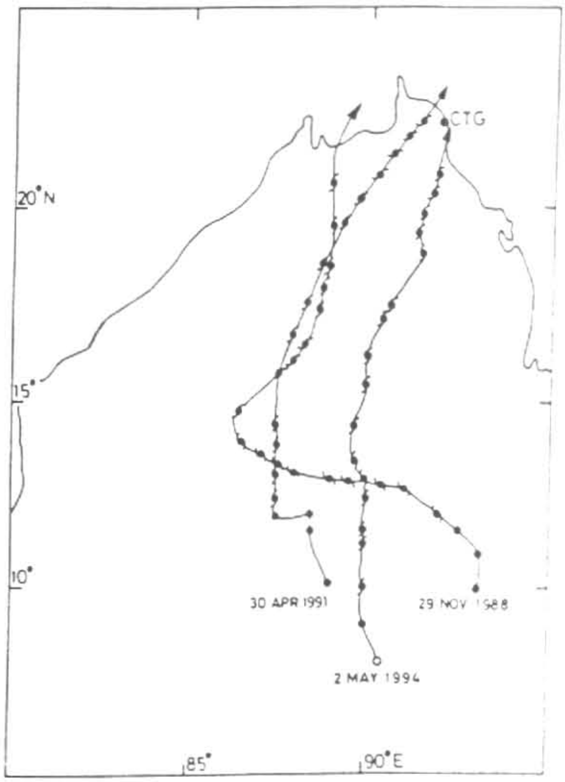


Fig. 1. Tracks of severe cyclonic storms with a core of hurricane winds of 29 November 1988, 30 April 1991 and 2 May 1994.

their fluxes over Bangladesh have been studied during the landfall of three major cyclones of 29 November 1988, 30 April 1991 and 2 May 1994. The cyclone of 29 November 1988 crossed Bangladesh coast near Raimangal river at about 1200 UTC. The cyclone of 30 April 1991 crossed Bangladesh coast a little north of Chittagong at 2000 UTC on 29 April and the one of 2 May 1994 crossed Teknaf coast at about 1500 UTC. The tracks of these cyclones are given in Fig.1.

2. Data used

The rawinsonde data of 0000 UTC at standard isobaric surfaces from 1000 to 100 hPa over Dhaka and Chittagong for six days in each of the cyclones have been considered. In cases where the surface pressure was below 1000 hPa, the data at the surface were considered for the computation of moisture, energy and their fluxes. For example, the surface pressure at Dhaka was found to be 998 and 994 hPa on 30 November 1988 and 30 April 1991 respectively. It may also be noted that the data at 300 hPa and above were not available on 30 April 1994 at Chittagong. To maintain the continuity, the gap has been filled up by taking the mean value of the data on 29 April and 1 May 1994.

3. Methodology

The use of the momentum and thermodynamic equations gives the total atmospheric energy per unit mass at any level. This total energy can be expressed as:

$$E = C_pT + gZ + L_q + 1/2\ V^2 \qquad (1)$$

Where, C_pT – Sensible heat per unit mass,

gZ – Potential energy per unit mass,

$C_pT + gz$ – Dry static energy per unit mass,

L_q – Latent energy per unit mass,

and $1/2\ V^2$ – Kinetic energy per unit mass.

'q' is the specific humidity.

The latent heat, L (cal gm^{-1}), is a function of temperature given by

$$L = 597.3 - 0.566\ (T\text{-}273) \qquad (2)$$

The total precipitable water (W) of the atmosphere is computed by using the relationship:

$$W = \frac{1}{g} \int_{P_T}^{P_0} q\ \mathrm{d}p \qquad (3)$$

The vertical integration is carried out upto 200 hPa by taking the mean specific humidity for each layer.

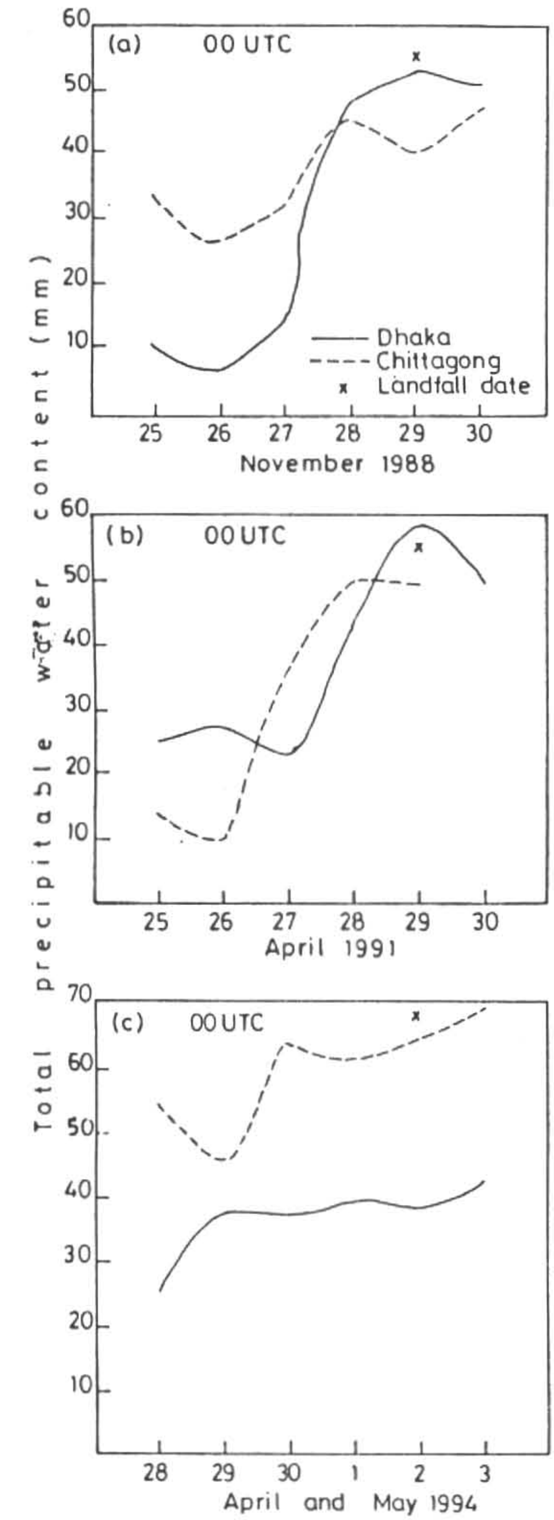
Following the Eqn.(3), vertical integrations have also been carried out for latent energy of the troposphere upto 200 hPa level, dry static energy and total energy of the troposphere upto 100 hPa level. This vertically-integrated energy has been expressed in kJ m^{-2}.

The zonal and meridional fluxes of any thermodynamic property (ϕ) can be expressed as:

$$F_z = \phi\ .u \qquad (4)$$

$$\text{and } F_m = \phi\ .v \qquad (5)$$

where, u and v are the zonal and meridional components of the wind vector **V**. The zonal and meridional fluxes of moisture (q), dry static energy ($C_pT + gZ$), latent energy (Lq) and total energy ($C_pT + gZ + Lq + 1/2V^2$) have been computed for each level and their vertical integrations have been made upto 200 hPa level for the fluxes of moisture and latent energy and upto 100 hPa level for other fluxes. The units of vertically-integrated moisture and energy fluxes are expressed in kg m^{-1}s^{-1} and kJ m^{-1}s^{-1} respectively. The positive values of zonal and meridional fluxes indicate westerly and southerly fluxes whereas the negative values of zonal and meridional fluxes indicate easterly and northerly fluxes respectively.



Figs.2(a-c). Total precipitable water content of the troposphere over Bangladesh during landfall of tropical cyclones of (a) 29 November 1988, (b) 30 April 1991 and (c) 2 May 1992.

TABLE 1

Difference between the highest and the lowest precipitable water content (mm) of the troposphere over Bangladesh during the landfall of tropical cyclones

S. No	Station	Precipitable water content (mm) in the cyclones of		
		November 1988	April 1991	May 1994
1.	Dhaka	46.4	36.3	16.6
2.	Chittagong	20.8	40.2	22.9

4. Results and discussion

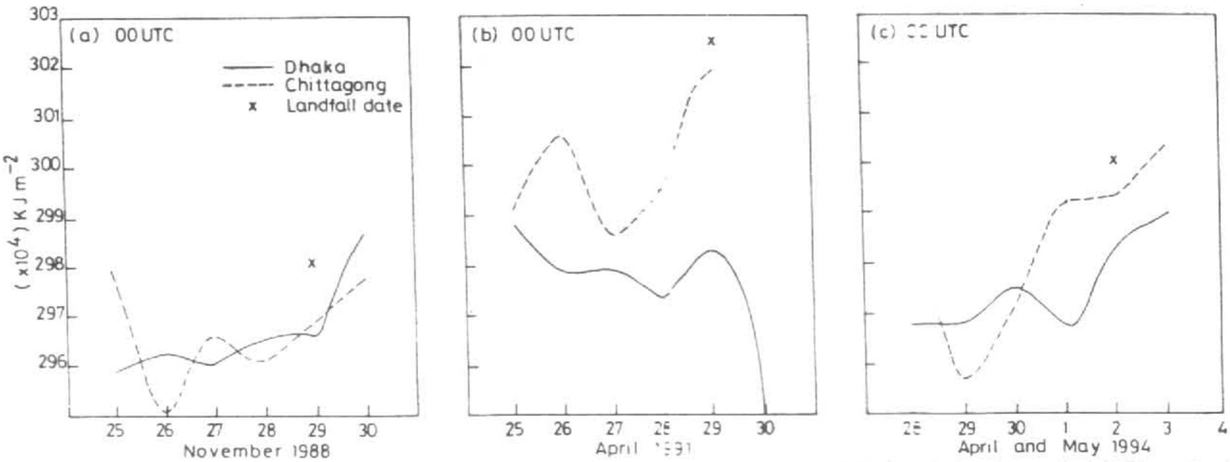
Because of the intensification of the cyclones advancing towards Bangladesh coast, significant moisture content extends upto 200 hPa level on some occasions. When the storm is closed to coast, the boundary layer is more rich in moisture. In the computation of vertically-integrated latent energy and the fluxes of moisture and latent energy, integration has been done upto 200 hPa level, whereas the integration of dry static energy, total energy and their fluxes has been carried out between the surface (1000 hPa and 100 hPa) level. The results are discussed in the following sub-sections.

4.1. *Total precipitable water content of the troposphere*

The Figs. 2(a-c) show the temporal variations of total precipitable water content (PWC) of troposphere over Bangladesh during the advancement of three cyclones for ultimate landfall at Bangladesh coast. It can be seen from the figures that the total PWC has a decreasing trend at the formative stages of the cyclones which could be attributed due to subsidence ahead of the cyclone in the environment. Then the total PWC in general, increases rapidly as the cyclones move towards the Bangladesh coast. The maximum PWC of the troposphere are 52.5 mm at Dhaka on 29 November 1988, 58.7 mm at Dhaka on 29 April 1991 and 68.4 mm at Chittagong on 3 May 1994. The difference between the highest and lowest values of PWC occurs near the tracks of the cyclones (Table 1).

4.2. *Vertically-integrated energy*

The vertically-integrated dry static energy, latent energy and total energy of the troposphere over Dhaka and Chittagong have been computed for the three case cyclones. Their temporal variations are shown in Figs.3(a-c), Figs.4(a-c) and Figs.5(a-c) respectively. It can be observed from the figures that they dry static energy, latent energy and total energy of the troposphere over Bangladesh at the formation stages of the cyclones show a general decreasing trend having a rapid increase with the advancement of the cyclones towards the coast except in case of dry static energy at Dhaka on 30 April 1991 where there is a sharp decrease. This exception has been due to the decrease in temperature and geopotential of the troposphere which can be attributed to the excessive precipitation over the area northwest of the



Figs.3 (a-c). Vertically-integrated dry static energy of the troposphere over Bangladesh during the landfall of tropical cyclones of (a) 29 November 1988, (b) 30 April 1991 and (c) 2 May 1994.

cyclone track between Chittagong and Dhaka and the presence of the upper air strong westerly trough. The general decreasing tendency of different types of energy over Bangladesh at the formation stages of the cyclones may be due to the subsidence ahead of the cyclones in the environment.

It has been found that the difference between the highest and lowest values of different energetics is maximum closed to the tracks of the cyclones. The differences between the highest and lowest values of the vertically-integrated dry static energy, latent energy and total energy are 2.8 x 10^4 kJm^{-2}, 11.5 x 10^4 kJm^{-2} and 13.2 x 10^4 kJm^{-2} respectively over Dhaka during November cyclone of 1988, 3.3 x 10^4 kJm^{-2}, 10.0 x 10^4 kJm^{-2} and 10.8 x 10^4 kJm^{-2} respectively over Chittagong during April cyclone of 1991 and 4.7 x 10^4 kJm^{-2}, 5.6 x 10^4 kJm^{-2} and 10.2 x 10^4 kJm^{-2} respectively over Chittagong during May cyclone of 1994. These show that the variation of dry static energy is less as compared to the latent energy and total energy.

4.3. *Vertically-integrated zonal and meridional fluxes of moisture*

The vertically-integrated zonal and meridional fluxes of moisture over Dhaka and Chittagong during the landfall of cyclones are given in Table 2. These fluxes obviously depend on the direction of wind at the station as the cyclone approaches. Table 2 shows that there exist westerly fluxes of moisture at the initial stages of the cyclones in the Bay of Bengal. These westerly fluxes gradually decrease significantly and become easterly in most of the cases except at Chittagong on 26 November 1988, Dhaka on 28 November 1988 and both at Dhaka and Chittagong on 1 May 1994. These exceptions can be attributed to the magnitudinal variations of the zonal wind components due to the intensity and the complex positional relationship of the cyclones in the Bay of Bengal and the moving westerly low across the northwestern part of Bangladesh and adjoining area. Then the easterly fluxes increase significantly as the cyclones move towards the coast. With the landfall of the cyclones, the easterly fluxes show tendency to be westerly again.

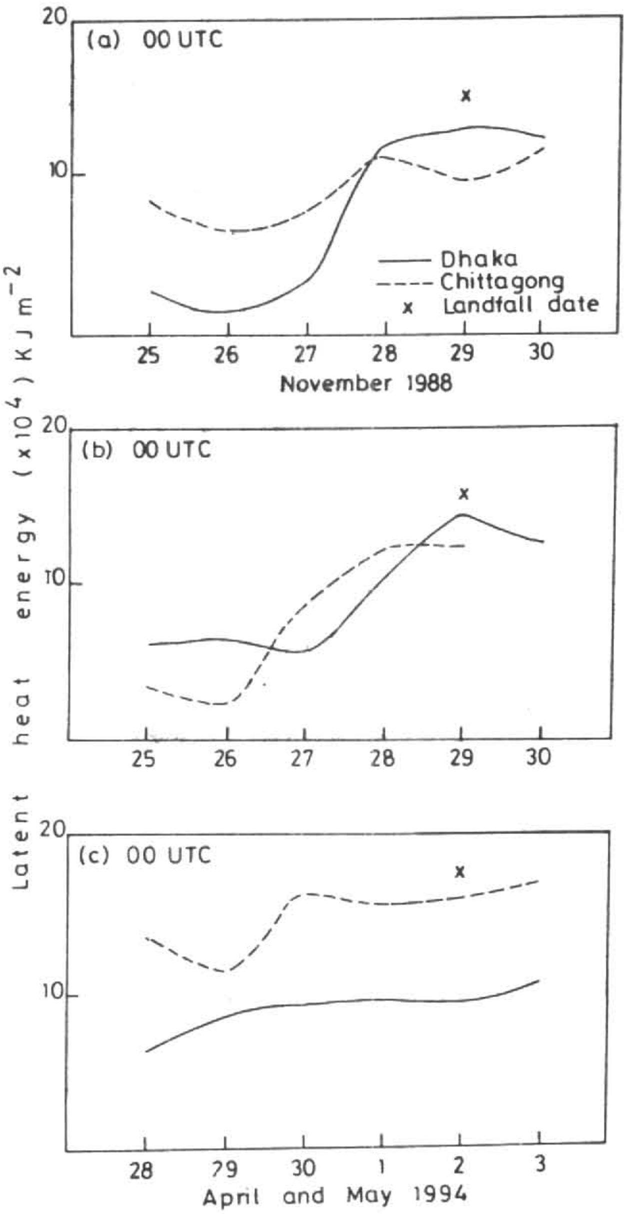
In case of meridional fluxes, there may be either northerly or southerly fluxes of moisture over Bangladesh at the formation stages of the cyclones. Initially, the meridional fluxes of moisture have tendency to decrease. As the cyclones move northwards, the northerly fluxes change into southerly fluxes which together with existing southerly fluxes increase significantly in almost all the cases except on 2 May 1994 when the southerly flux decreases at Chittagong and the flux is northerly at Dhaka (Table 2). This anomalous behaviour of the fluxes is due to the dominating easterly component of the zonal flow upto 500 hPa level at Dhaka and Chittagong. After landfall of the cyclones, the southerly fluxes become northerly again except at Chittagong on 30 November 1988 in which case the movement of the cyclone was in a northeasterly direction across Bangladesh after crossing the Sunderban coast.

4.4. *Vertically-integrated zonal and meridional fluxes of energy*

4.4.1. *Fluxes of dry static energy*

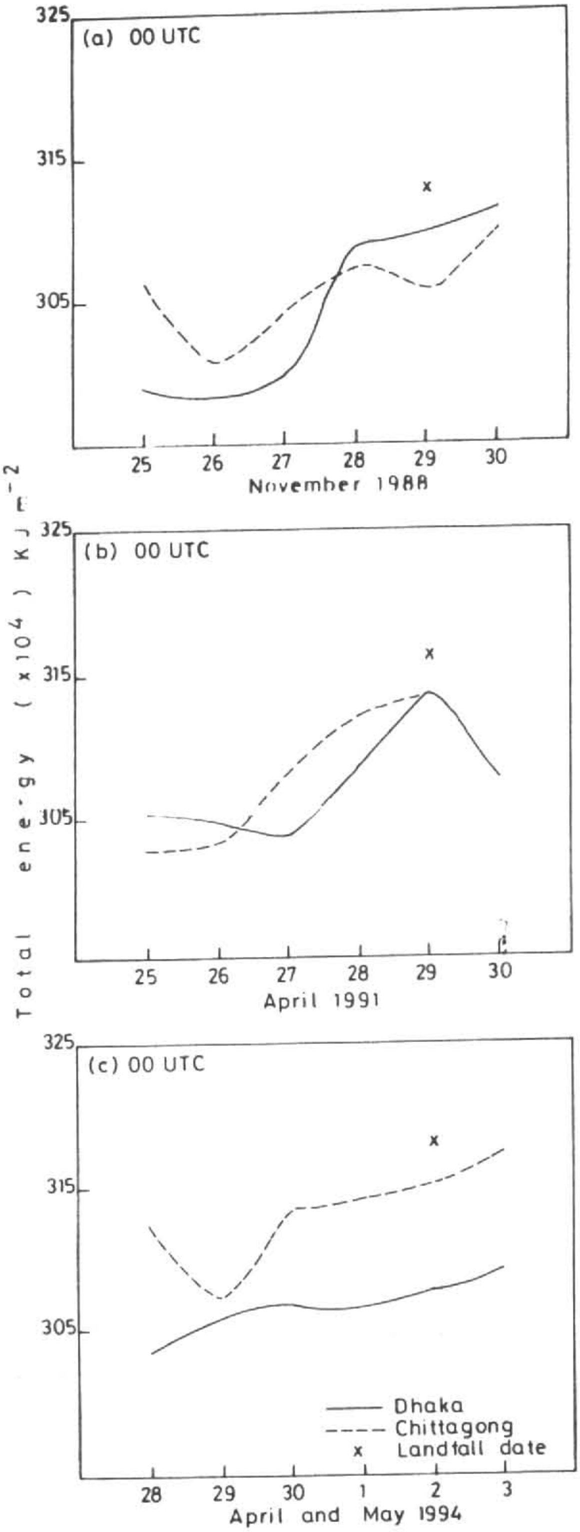
The vertically-integrated zonal and meridional fluxes of dry static energy are given in Table 3. Table 3 clearly shows that the zonal fluxes of dry static energy are westerly which decrease significantly as the cyclones move towards Bangladesh coast with an exception at Dhaka on 26 November 1988. The westerly fluxes may even change into easterly fluxes prior to the landfall of cyclones. After the landfall of cyclones, the persisting westerly fluxes increase considerably and the easterly fluxes become westerly.

Table 3 shows the presence of mainly southerly fluxes of dry static energy over Dhaka and Chittagong for almost all the cyclones before their landfall except at Dhaka on 25 November 1988 and both at Dhaka and Chittagong on 25



Figs.4 (a-c). Vertically-integrated latent heat energy of the troposphere over Bangladesh during the landfall of tropical cyclones of (a) 29 November 1988, (b) 30 April 1991 and (c) 2 May 1994.

April 1991 when the fluxes are northerly. These northerly fluxes become southerly which, together with the prevailing southerly fluxes, increase significantly with the advancement of the cyclones towards the coast having some exceptions when there exist a decrease in southerly fluxes on or before the landfall dates such as at Dhaka on 27 November 1988 and 1-2 May 1994 and at Chittagong on 2 May 1994. The exception at Dhaka on 27 November 1988 is due to the sudden increase of the northerly fluxes at 500 hPa level. This sudden increase in the northerly fluxes can be attributed to the incursion of a strong ridge upto Calcutta and the interaction of westerly low with the impending cyclone. In case of 1-2 May 1994 at Dhaka and of 2 May 1994 at Chittagong,



Figs.5 (a-c). Vertically-integrated total energy of the troposphere over Bangladesh during the landfall of tropical cyclones of (a) 29 November 1988, (b) 30 April 1991 and (c) 2 May 1994.

TABLE 2

Vertically-integrated (a) zonal and (b) meridional fluxes of moisture (x cross kg m^{-1} s^{-1}) of the troposphere over Bangladesh during the landfall of tropical cyclones

November 1988 cyclone			April 1991 cyclone			April-May 1994 cyclone		
Date November 1988	Fluxes at		Date April 1991	Fluxes at		Date April-May 1994	Fluxes at	
	Dhaka	Chittagong		Dhaka	Chittagong		Dhaka	Chittagong
				(a) Zonal fluxes				
25	+23.0	+6.8	25	+113.4	+7.0	April 28	+82.5	+89.6
26	+5.3	+61.7	26	+35.6	-28.5	29	+55.0	+45.2
27	-25.4	-18.6	27	-16.4	-2.3	30	-14.8	-8.9
28	+103.0	- 121.2	28	-74.6	-91.8	May 1	+39.1	+142.0
29	- 176.3	- 270.5	29	- 187.6	- 303.7	2	- 143.4	- 318.1
30	+783.2	- 469.9	30	+99.1	-	3	+103.1	+398.6
				(b) Meridional fluxes				
25	-63.2	+24.9	25	+79.4	+80.0	April 28	-3.8	- 134.8
26	-11.4	-12.9	26	+60.7	+20.0	29	+18.8	+23.8
27	+23.5	-0.2	27	+37.6	+110.7	30	+55.9	+151.6
28	+319.7	+267.8	28	+82.5	+449.2	May 1	+61.6	+157.0
29	+459.9	+217.5	29	+242.0	+561.8	2	- 54.3	+26.3
30	- 117.5	+826.7	30	- 637.7	-	3	- 214.9	- 475.1

TABLE 3

Vertically-integrated (a) zonal and (b) meridional fluxes of dry static energy (x 10^{4} kJ m^{-1} s^{-1}) of the troposphere over Bangladesh during the landfall of tropical cyclones

November 1988 cyclone			April 1991 cyclone			April-May 1994 cyclone		
Date November 1988	Fluxes at		Date April 1991	Fluxes at		Date April-May 1994	Fluxes at	
	Dhaka	Chittagong		Dhaka	Chittagong		Dhaka	Chittagong
				(a) Zonal fluxes				
25	+4818.0	+1837.3	25	+4862.9	+4958.4	April 28	+3673.0	+3834.2
26	+5272.4	+1326.2	26	+4146.8	+4194.3	29	+3413.0	+3531.7
27	+3184.2	+847.3	27	+2598.7	+2622.4	30	+3146.2	+2361.8
28	+2565.4	-203.1	28	+1580.7	+2287.2	May 1	+1992.2	+2377.2
29	+1161.9	- 1080.8	29	+544.3	-257.5	2	-32.5	-698.2
30	+5779.8	+390.8	30	+1392.0	-	3	+1091.1	+1949.2
				(b) Meridional fluxes				
25	-71.5	+1341.1	25	-63.8	- 332.0	April 28	+1417.5	+1244.4
26	+1616.2	+1814.6	26	+943.8	+1069.9	29	+1384.9	+1723.1
27	+1605.6	+1545.9	27	+1199.3	+1710.5	30	+2503.3	+2615.0
28	+2600.5	+3386.1	28	+2083.9	+3162.1	May 1	+1900.3	+2921.6
29	+3399.2	+2708.2	29	+2899.3	+4887.3	2	+1064.0	+1534.7
30	-444.3	+3951.3	30	- 2405.2	-	3	- 1212.4	- 2492.6

the exceptions are due to the dominating easterly component thereby decreasing the southerly component. After the landfall of cyclones, the southerly fluxes of dry static energy change into northerly fluxes except on 30 November 1988 at Chittagong. The reason for this exception has already mentioned earlier.

4.4.2. *Fluxes of latent energy*

The zonal and meridional fluxes of latent energy are given in Table 4. Although there exist some anomalies like zonal fluxes of moisture, the westerly fluxes of latent energy have decreasing tendency and become easterly during the landfall of cyclones. After the landfall of cyclones, the fluxes of latent energy become westerly again except at Chittagong on 30 November 1988 when the flux is easterly. This is due to the movement of the cyclone with almost the same intensity across Bangladesh towards northeast.

At the initial stages of the cyclones, the meridional fluxes of latent energy have the same conditions as those of

TABLE 4

Vertically-integrated (a) zonal and (b) meridional fluxes of latent energy (x 10^4 kJ m^{-1} s^{-1}) of the troposphere over Bangladesh during the landfall of tropical cyclones

November 1988 cyclone			April 1991 cyclone			April-May 1994 cyclone		
Date November 1988	Fluxes at		Date April 1991	Fluxes at		Date April-May 1994	Fluxes at	
	Dhaka	Chittagong		Dhaka	Chittagong		Dhaka	Chittagong
(a) Zonal fluxes								
25	+5.6	+1.8	25	+28.0	+1.7	April 28	+20.6	+22.8
26	+1.3	+15.2	26	+8.9	- 6.9	29	+13.8	+11.8
27	- 6.2	- 4.6	27	-3.9	- 0.2	30	- 3.3	- 0.8
28	+26.2	- 29.6	28	-18.0	- 21.4	May 1	+9.8	+35.6
29	- 43.1	- 66.8	29	-46.1	- 74.9	2	- 35.2	- 78.2
30	+193.8	- 116.1	30	+24.8	-	3	+25.4	+98.5
(b) Meridional fluxes								
25	- 15.5	+6.1	25	+19.3	+19.5	April 28	-0.7	- 33.1
26	- 2.8	- 3.0	26	+14.8	+4.9	29	+4.4	+6.0
27	+5.8	+0.2	27	+9.2	+27.2	30	+14.1	+38.2
28	+81.5	+66.5	28	+20.8	+110.9	May 1	+15.3	+39.2
29	+114.3	+54.3	29	+60.6	+139.9	2	- 13.2	- 7.1
30	-28.9	+204.6	30	- 157.8	-	3	- 52.9	- 117.9

TABLE 5

Vertically-integrated (a) zonal and (b) meridional fluxes of total energy (x 10^4kJ $m^{-1}s^{-1}$) of the troposphere over Bangladesh during the landfall of tropical cyclones

November 1988 cyclone			April 1991 cyclone			April-May 1994 cyclone		
Date November 1988	Fluxes at		Date April 1991	Fluxes at		Date April-May 1994	Fluxes at	
	Dhaka	Chittagong		Dhaka	Chittagong		Dhaka	Chittagong
(a) Zonal fluxes								
25	+4829.2	+1839.6	25	+4895.8	+4966.2	April 28	+3698.7	+3863.3
26	+5280.6	+1341.7	26	+4159.8	+4191.2	29	+3431.0	+3547.8
27	+3182.3	+843.0	27	+2596.5	+2624.6	30	+3147.6	+2363.5
28	+2595.2	-234.9	28	+1563.7	+2268.0	May 1	+2003.5	+2414.6
29	+1120.6	- 1145.4	29	+498.4	-332.3	2	-67.5	-776.4
30	+5979.2	+281.4	30	+1417.4	-	3	+1116.3	+2048.1
(b) Meridional fluxes								
25	- 86.2	+1347.7	25	-44.1	-314.5	April 28	+1419.4	+1215.2
26	+1616.5	+1812.0	26	+959.9	+1076.3	29	+1391.5	+1731.8
27	+1613.8	+1546.6	27	+1209.4	+1739.3	30	+2520.6	+2655.7
28	+2685.6	+3459.6	28	+2105.7	+3275.2	May 1	+1916.9	+2963.2
29	+3516.1	+2753.9	29	+2970.5	+5030.7	2	+1051.2	+1542.4
30	-477.5	+4152.7	30	- 2562.2	-	3	- 1265.5	- 2611.2

moisture. Besides these, the southerly fluxes of latent energy have increasing trend before the landfall of cyclones except on 29 November 1988 at Dhaka and on 1-2 May 1994 at Dhaka and Chittagong. The reasons for these anomalies have already been mentioned. The southerly fluxes become northerly after the landfall of cyclones except at Chittagong on 30 November 1988 when the flux is still southerly having larger magnitude. This exception is due to the same reason as mentioned earlier.

4.4.3. *Fluxes of total energy*

Table 5 represents the vertically-integrated zonal and meridional fluxes of total energy. The westerly fluxes of total energy of the troposphere over Bangladesh exhibit a significant decreasing trend before the landfall of cyclones with some exceptions as mentioned earlier in the case of zonal fluxes of dry static energy. The changing patterns of the fluxes of total energy are also similar to those of the zonal fluxes of dry static energy. The variations of the meridional fluxes of total energy are identical with those of dry static energy, the only difference being in magnitudes.

5. Conclusions

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

(*i*) The total precipitable water content of the troposphere over Bangladesh has a decreasing trend at the formation stages of the cyclones in the Bay of Bengal. This may be due to subsidence ahead of the cyclone in the environment. The precipitable water increases rapidly as the cyclones move towards the coast. Maximum increase in moisture occurs near the tracks of the cyclones.

(*ii*) The vertically-integrated dry static energy, latent energy and total energy of the troposphere over Bangladesh exhibit decreasing tendency at the formation stages of the cyclones and then they increase significantly with the advancement of the cyclones towards the coast. Maximum increase in different energetics occurs near the tracks of the cyclones.

(*iii*) The vertically-integrated zonal fluxes of moisture, dry static energy, latent energy and total energy in the troposphere over Bangladesh are westerly at the initial stages of the cyclones in the Bay of Bengal. With the advancement of the cyclones towards the coast, these westerly fluxes decrease and may even change into easterly fluxes. The decrease in the zonal fluxes of dry static energy and total energy is very significant. The persisting westerly fluxes of moisture and different energetics increase again or the easterly fluxes change into westerly fluxes after the landfall of the cyclones.

(*iv*) The vertically-integrated meridional fluxes of moisture, dry static energy, latent energy and total energy in the troposphere over Bangladesh may be either northerly or southerly at the formation stages of the cyclones. As the cyclones move towards the coast, the northerly fluxes change into southerly fluxes which, together with the persisting southerly fluxes, increase significantly prior to the landfall of cyclones. The fluxes have a tendency to be northerly after the landfall of cyclones.

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