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On the zonal and meridional eddy flux of energy components of the troposphere over the Arabian Sea during the onset phase of SW monsoon

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सार — मॉनेक्स- 79 में अरबसागर पर राविनसोन्दे से संग्रहीत आंकड़ों को द० प० मानसून की शुरुआत की अवस्था में अरबसागर के क्षोभमंडल की शुष्क स्थितिक एवं नम स्थितिक ऊर्जा के क्षेत्रीय एवं याम्योत्तरीय अभिवाहों के अध्ययन का उपयोग किया गया है। अध्ययनों से स्पष्ट होता है कि शुष्क स्थितिक ऊर्जा के क्षेत्रीय भँवर अभिवाह ऊँचाई के अनुसार विषम रूप से बंटित हैं। नम स्थितिक ऊर्जा के पूर्वी भँवर अभिवाह मानसून की शुरुआत की अवस्था में प्रभावी रहते हैं और 900-600 मि०बार की परत में इनका मान अधिकतम होता है। मानसून की सक्रियता में वृद्धि से गुप्त ऊष्मा के भँवर अभिवाह के अंशदान को ही खास वजह से शुष्क स्थितिक के क्षेत्रीय भँवर अभिवाहों और नम स्थितिक ऊर्जा के माध्य-परिमाण में अन्तर स्पष्ट है। 60° पू० के पूर्व में शुष्क स्थितिक ऊर्जा का दक्षिणी भँवर अभिवाह 700 मि० बार पर अधिकतम होता है। और लगभग 7° उ० पर उत्तर दिशा की ओर जाता हुआ दिखने लगता है। नम स्थितिक ऊर्जा का उत्तरी भँवर अभिवाह 7° उ० या उससे नीचे होने पर 700 मि० बार तक द० प० मानसून के अग्रगमन के साथ अधिक नीचे को ओर फैलता जाता है।

ABSTRACT. The rawinsonde data collected during the Arabian Sea phase of the MONEX-79 have been utilized to study the zonal and meridional eddy fluxes of dry static and moist static energy of the troposphere over the Arabian Sea during the onset phase of SW-Monsoon. The study reveals that the zonal eddy flux of dry static energy is irregularly distributed with height whereas the eastward eddy flux of moist static energy becomes dominant during the onset phase of monsoon having maximum value within the layer 900-600 mb. There exists a well-marked magnitudinal difference between the zonal eddy fluxes of dry static and moist static energy due mainly to the contribution of eddy flux of latent heat with increasing monsoon activity. To the east of 60° E, the maximum southward eddy flux of dry static energy at 700 mb roughly along 7 °N shows the tendency to be northward and the northward eddy flux of moist static energy along 7° N and below extends to 700 mb or further downward with the advancement of SW-Monsoon.

1. Introduction

Studies on meridional fluxes of energy have received attention of the scientists for its important contribution in maintaining the general circulation of the atmosphere. The computation of meridional eddy transfer of heat based on observational data was carried out by Priestly (1949). Holopainen (1965) studied the role of mean meridional circulation in the energy balance of the atmosphere and found a great difference between tropics and the extra-tropics with respect to the mechanism of the flux. Not much studies were carried out, in the past, on fluxes of energy and moisture with respect to the onset of monsoon except a few among which works of Rao and Sastry (1953), Anjaneyulu (1969, 1971) and Ghosh *et al*. (1978) can be cited. In the present paper the authors have made an attempt to study the zonal and meridional eddy fluxes of energy (dry and moist static) based on MONEX-79 data over the Arabian Sea during the onset phase of summer monsoon (hereinafter called monsoon only).

2. Basic considerations

The equations considered for calculation of zonal eddy fluxes of energy are :

$$\overline{(c_p\,T + gz)'u'} = \overline{(c_p\,T + gz)u} - \overline{(c_p\,T + gz)}\,.\,\overline{u} \tag{1}$$

and

$$\overline{(c_p\,T + gz + Lq)'u'} = \overline{(c_p\,T + gz + Lq)\,u} - \overline{(c_p\,T + gz + Lq)}\,.\,\overline{u} \tag{2}$$

where T is the temperature, gz the potential energy per unit mass, u the zonal wind component c_p the specific heat of air at constant pressure, Lq the latent heat per unit mass and the primes are the deviations from the means.

Similarly, the equations for calculation of meridional eddy fluxes of energy are :

$$\overline{(c_p\,T + gz)'\,v'} = \overline{(c_p\,T+gz)\,v} - \overline{(c_p\,T + gz)}\,.\,\overline{v} \tag{3}$$

and

$$\overline{(c_p\,T + gz + Lq)'\,v'} = \overline{(c_p\,T + gz + Lq)\,v} - \overline{(c_p\,T + gz + Lq)}\,.\,\overline{v} \tag{4}$$

where v is the meridional wind component.

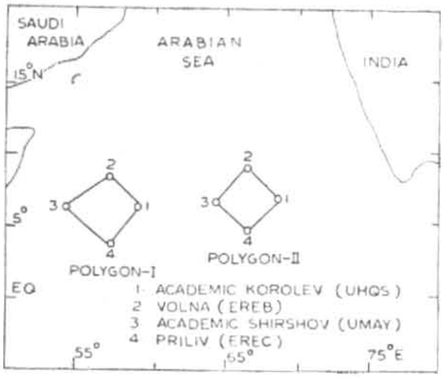
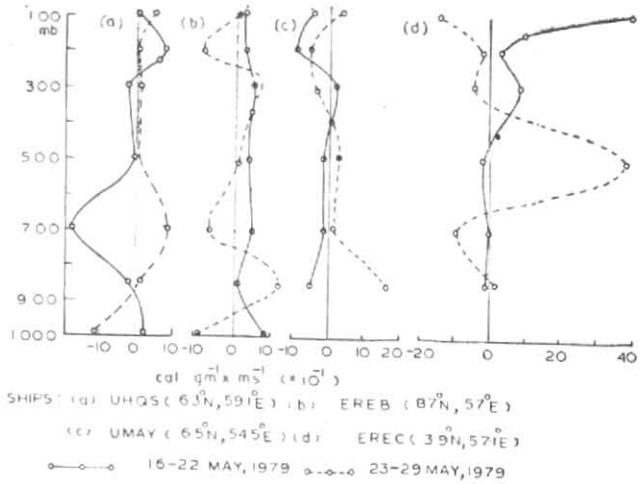
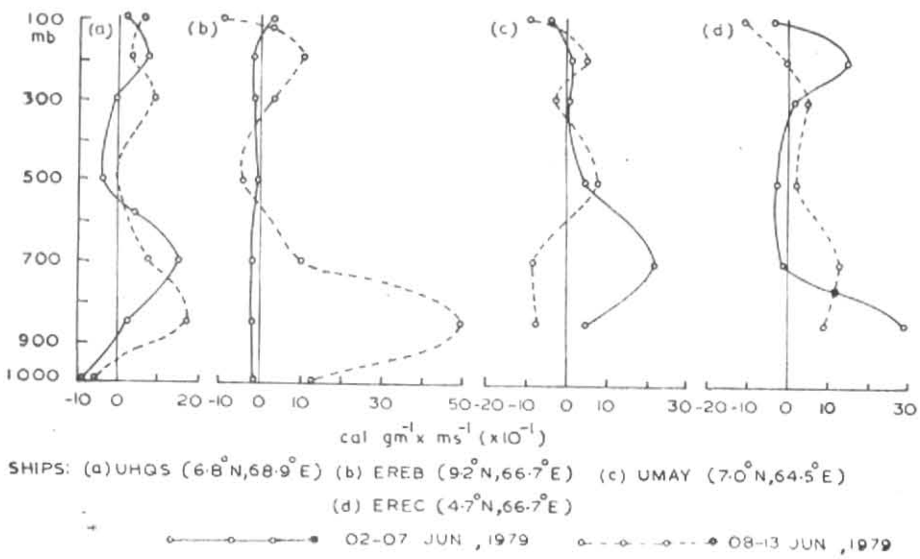


Fig. 1. Location of Monex ships



Figs.2 (a-d). Weekly zonal eddy flux of moist static energy



Figs. 3 (a-d). Weekly zonal eddy flux of moist static energy

3. Data source

The rawinsonde data based on 1200 GMT observations for standard isobaric heights from 1000 mb to 100 mb levels on board the ships forming polygons I and II of periods 16-29 May and 02-13 June 1979 respectively have been utilized in the present study. The locations of the ships are shown in Fig. 1. Within the range of the study periods, the non-continuous nature of the data for some occasions have been overcome by considering data of nearest synoptic hours. The effect of this fill-up effort on the final results has been observed to be insignificant. Nevertheless, this introduces some uncertainty in the present study. The weekly period considered for polygon I covers 7 days whereas the same for polygon II consists of 6 days except in case of ship *EREB* where it is of 5 days only.

4. Results and discussions

4.1. *Zonal eddy flux of dry static and moist static energy* ; The weekly zonal eddy fluxes of dry static and moist static energy are calculated for polygons I and II, and results are shown in Tables 1 and 2 respectively. From Table 1 it is observed that the distribution of weekly zonal eddy flux of dry static energy is mainly irregular with height. Similarly, the irregularity is observed in the vertical distribution of moist static energy during both the weeks of polygon I as shown in Figs. 2 (a-d) and there is a change of sign from one week to another in the layers roughly below 500 mb. It is also observed that the distribution is positive (eastward) broadly in the middle troposphere during second week. In case of polygon II, it is importantly noted that the distribution of weekly zonal eddy flux of moist static energy, shown in Figs. 3 (a-d), is predominantly eastward in the lower troposphere with maximum value between 900 mb and 600 mb approaching a minimum between 600 mb and 400 mb except in ships *ERER* and *UMAY* wherein the value is westward and eastward respectively in the lower troposphere. A secondary positive (eastward) value is also found to exist roughly

TABLE 1

Weekly zonal eddy flux of dry static energy in cal $gm^{-1} \times ms^{-1} (\times 10^{-1})$

Ship	Levels (mb)	$\overline{(c_pT+gz)' u'}$			
		16-22 May	23-29 May	02-07 June	08-13 June
UHQS	1000	—2.08	—2.46	+0.88	+5.28
	850	—3.30	+3.92	+1.38	—9.42
	700	—5.80	+6.42	+1.65	—0.14
	500	—0.60	+5.76	—1.62	—0.42
	300	—2.86	+0.89	—0.22	+8.28
	200	+7.90	+0.06	+7.86	+3.45
	100	+0.04	+4.83	+2.22	+6.72
EREB	1000	—0.34	—1.29	—2.49	—7.34
	850	+2.31	—2.72	+0.14	+12.19
	700	+3.66	+2.44	+4.54	+4.61
	500	+3.63	—3.45	+2.13	+0.64
	300	+4.66	+7.58	—0.61	+3.00
	200	+2.75	—8.78	—1.62	+11.14
	100	+2.51	+1.92	+3.92	—9.12
UMAY	1000	—	—	—	—
	850	+0.62	+8.28	+6.47	—11.18
	700	+1.62	+9.04	+6.55	—5.77
	500	—2.10	+0.90	+4.96	+4.33
	300	—0.83	—4.03	+0.71	—3.05
	200	—9.11	—5.22	+1.12	+4.65
	100	—4.77	+3.07	—4.40	—9.82
EREC	1000	—	—	—	—
	850	+2.02	+4.83	+3.88	+8.88
	700	—2.04	—4.95	—2.60	+9.55
	500	+0.39	—1.68	—0.44	—1.89
	300	+6.57	—4.08	+0.39	+1.96
	200	+2.19	—2.50	+14.91	—0.58
	100	+38.93	—15.22	—3.60	—11.39

TABLE 2

Weekly zonal eddy flux of moist static energy in cal $gm^{-1} \times ms^{-1} (\times 10^{-1})$

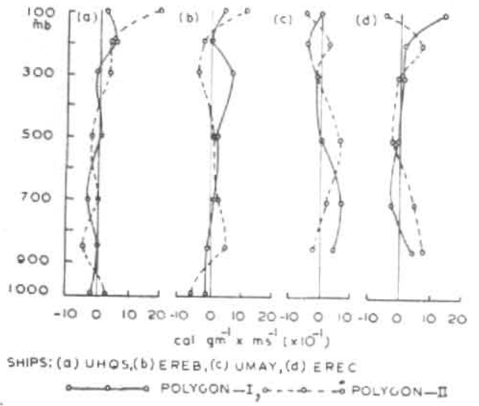
Ship	Level (mb)	$\overline{(c_pT+gz+Lq)'u'}$			
		16-22 May	23-29 May	02-07 June	08-13 June
UHQS	1000	+2.61	—11.33	—9.25	—6.37
	850	—2.10	+1.48	+2.25	+17.14
	700	—17.62	+9.17	+14.81	+7.41
	500	—0.16	+0.86	—3.89	—0.25
	300	—2.06	+1.18	—0.23	+9.39
	200	+7.90	+0.06	+7.86	+3.45
	100	+0.04	+4.83	+2.22	+6.72
EREB	1000	+8.80	—10.55	—1.38	+11.81
	850	+0.66	+12.55	—2.19	+50.09
	700	+5.17	—7.12	—1.92	+9.99
	500	+3.92	+1.51	—0.44	—4.13
	300	+5.43	+7.40	—1.06	+3.64
	200	+2.75	—8.78	—1.62	+11.14
	100	+2.51	+1.92	+3.92	—9.12
UMAY	1000	—	—	—	—
	850	—4.80	+16.34	+4.57	—7.66
	700	—0.90	+1.44	+21.45	—8.51
	500	—1.07	+2.90	+3.99	+7.37
	300	+2.07	—4.20	+0.49	—3.15
	200	—9.11	—5.22	+1.12	+4.65
	100	—4.77	+3.07	—4.40	—9.82
EREC	1000	—	—	—	—
	850	—1.85	+1.28	+28.95	+8.65
	700	—1.08	—10.31	—1.56	+12.45
	500	—2.44	+37.38	—2.89	+1.95
	300	+7.70	—5.03	+1.57	+4.58
	200	+2.19	—2.50	+14.91	—0.58
	100	+38.93	—15.22	—3.60	—11.39

around 200 mb except in ship *EREB*. While the exceptions in case of *EREB* and *UMAY* could not be explained, it is evident from other ships of this ploygon that the dominance of eastward eddy flux both in lower and upper tropospheres is due to the nearing of the date of onset of monsoon.

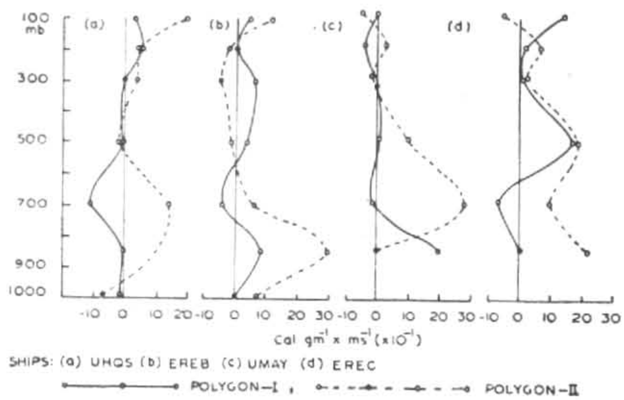
Considering the whole period for each polygon, *i.e.,* 16-29 May and 02-13 June 1979 for polygon I and polygon II respectively, it is also seen from Figs. 4 (a-d) that the zonal eddy flux of dry static energy is irregularly distributed with height. But in case of zonal eddy flux of moist static energy, as shown in Figs. 5 (a-d), the distribution is not so irregular with height. In fact, the zonal eddy flux of moist static energy in polygon II is significantly greater as compared to that in polygon I and it is prominently eastward roughly from surface to about middle troposphere, sometimes far beyond having maxima between 900 and 650 mb. Comparing Figs. 5 (a-d) with Figs. 4 (a-d) for polygon II, one finds that there exists a well-marked magnitudinal difference between two types of zonal eddy fluxes (dry static and moist static). This difference is mainly due to the major contribution from eddy flux of latent heat energy which is related to the advancement of monsoon.

4.2. *Meridional eddy flux of dry static and moist static energy*: As can be seen from Table 3 and Figs. 6 (a & c) and 7 (a & c), wherein the ship positions are roughly at the same latitude (6.3-7.0 N), there exists a general pattern in the vertical distribution of meridional eddy flux of dry static energy from one week to another with the advancement of monsoon. It is observed that the flux is poleward (positive) in the middle troposphere in both the polygons except for first week in ship *UMAY* where the distribution is though not positive but close to zero, and the magnitudinal difference from first week to the second week is less in polygon II than that in polygon I. Again the fluxes show distinct negative maxima at about 700 mb during second weeks of both polygons, the magnitude being also less in polygon II than that in polygon I. It is, however, at present not reasonable to term this distribution as a regular feature without having further study with more data in future.

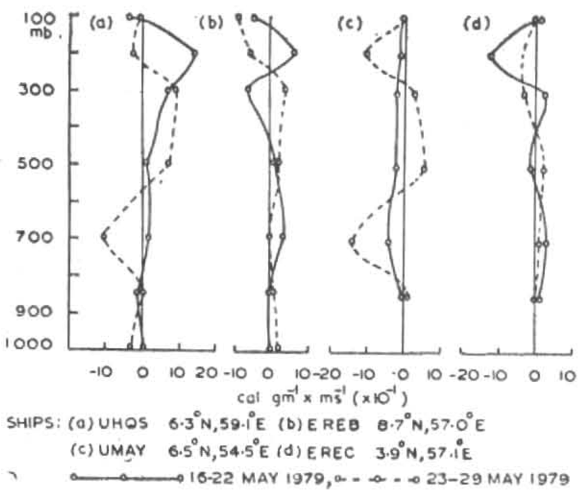
Considering Table 3 and the Figs. 6 (b & d), wherein the ships are at about the same longitude (57.1 E), the eddy flux of dry static energy in the second week is broadly positive (northward) and generally regular upto about 400 mb level, then gradually becomes negative (equatorward), whereas in the first week the distribution is a bit irregular. But in both the weeks, the flux values are found to be smaller in magnitude. It is, however, of interest to note that the eddy fluxes are quite strong in polygon II in both the weeks as shown in Table 3 and Figs. 7 (b & d), wherein the ships are at the same longitude (66.7 E). The flux distribution of polygon II during first



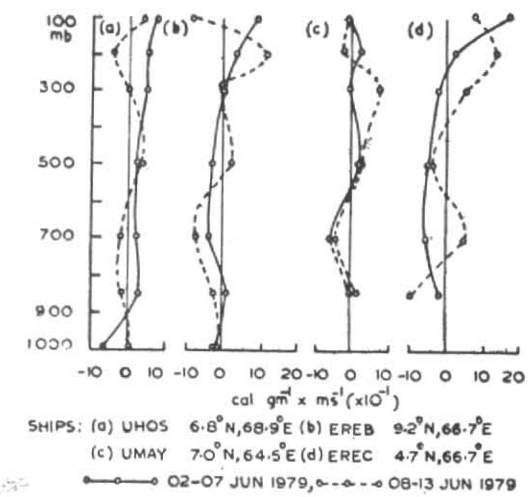
Figs. 4 (a-d). Zonal eddy flux of dry static energy



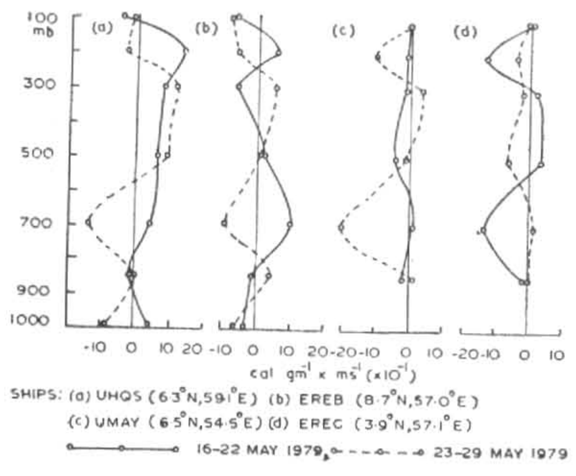
Figs. 5 (a-d). Zonal eddy flux of moist static energy



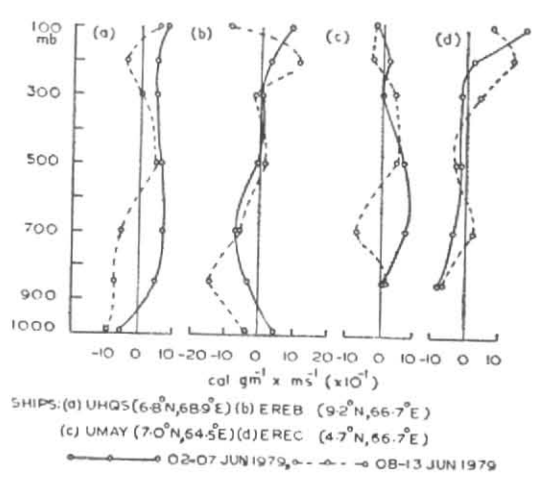
Figs. 6 (a-d). Weekly meridional eddy flux of dry static energy



Figs. 7 (a-d). Weekly meridional eddy flux of dry static energy



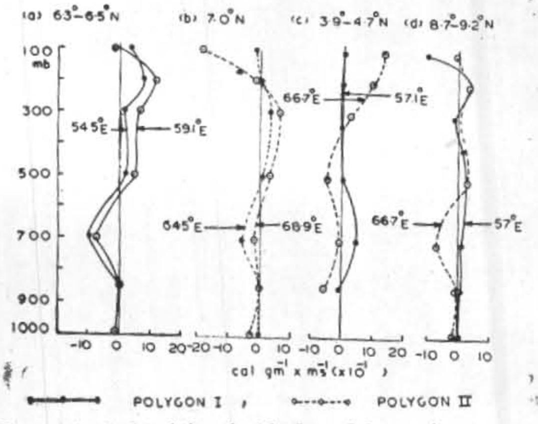
Figs. 8 (a-d). Weekly meridional eddy flux of moist static energy



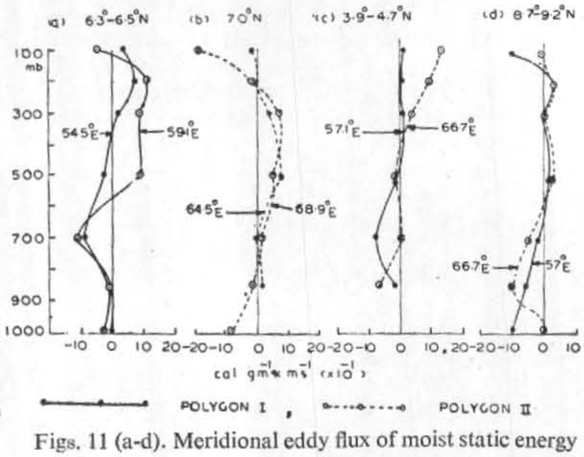
Figs. 9 (a-d). Weekly meridional eddy flux of moist static energy

week is quite regular maintaining negative sign (southward) roughly from 850 mb to 300 mb levels with maximum at 700 mb. During the second week, though the flux shows a little irregular distributon, it mainly exhibits equatorward trend upto about middle troposphere.

The vertical variation of weekly meridional eddy flux of moist static energy is shown in Figs. 8 (a-d) and 9 (a-d) with Table 4. It can be observed from Figs. 8 (a & c) that the distribution during second week of polygon I shows marked difference than that of the first week. In the second sweek, negative flux (southward) generally exists between 1000-900 mb, 850-550 mb and 250-100 mb attaining maxima at 700 mb and 200 mb levels, the highest being at 700 mb level.



Figs. 10 (a-d). Meridional eddy flux of dry static energy



Figs. 11 (a-d). Meridional eddy flux of moist static energy

TABLE 3

Weekly meridional eddy flux of dry static energy in cal $gm^{-1} \times ms^{-1}$ ($\times 10^{-1}$)

Ship	Level (mb)	$\overline{(c_pT+gz)'v'}$ 16-22 May	23-29 May	02-07 June	08-13 June
UHQS	1000	+0.95	−3.12	−6.72	+0.29
	850	−1.08	+0.12	+2.59	−1.78
	700	+1.69	−10.33	+2.31	−1.93
	500	+1.23	+7.35	+2.80	+3.35
	300	+7.22	+9.35	+5.21	+0.22
	200	+14.17	−2.01	+5.30	−3.73
	100	−3.51	−0.56	+8.15	+5.14
EREB	1000	−0.20	+1.52	−2.45	−2.19
	850	−0.77	+0.37	+0.80	−3.01
	700	+3.18	−0.66	−4.15	−7.69
	500	+0.86	+1.63	−3.01	+1.98
	300	−0.61	+4.04	−0.01	−0.67
	200	+6.53	−5.30	+3.20	+11.94
	100	−5.54	−9.01	+9.62	−8.50
UMAY	1000	—	—	—	—
	850	−0.12	+1.12	−0.06	+1.38
	700	−4.32	−14.03	−5.89	−4.92
	500	−2.02	+5.46	+2.10	+2.23
	300	−1.43	+2.89	−0.83	+7.26
	200	−0.84	−10.01	+2.21	−2.38
	100	+0.05	+0.25	−1.12	−1.45
EREC	1000	—	—	—	—
	850	+1.06	+0.22	−1.95	−9.92
	700	+3.08	+1.17	−5.70	+4.51
	500	−1.19	+2.15	−5.10	−4.05
	300	+2.65	−3.12	−1.97	+5·10
	200	−12.56	−3.27	+2.09	+13.71
	100	+1.39	+0.29	+17.83	+7.64

TABLE 4

Weekly meridional eddy flux of moist static energy in cal $gm^{-1} \times ms^{-1}$($\times 10^{-1}$)

Ship	Level (mb)	$\overline{(c_pT+gz+Lq)'v'}$ 16-22 May	23-29 May	02-07 June	08-13 June
UHQS	1000	+4.35	−8.93	−6.78	−9.92
	850	−1.59	+0.30	+4.95	−7.23
	700	+4.78	−13.79	+7.09	−5.08
	500	+6.77	+9.34	+6.15	+5.15
	300	+8.48	+12.03	+5.15	+0.93
	200	+14.17	−2.01	+5.30	−3.73
	100	−9.96	−0.56	+8.15	+5.14
EREB	1000	−3.92	−6.78	+4.53	−0.36
	850	−1.27	+4.18	−3.09	−14.13
	700	+10.27	−9.11	−6.69	−5.63
	500	+1.84	+1.42	−0.34	+1.98
	300	−5.51	+5.51	+0.67	−0.83
	200	+6.53	−5.30	+3.20	+11.94
	100	−5.54	−7.20	+9.62	−8.50
UMAY	1000	—	—	—	—
	850	−1.72	+1.64	+1.21	+1.70
	700	+1.35	−19.68	+7.74	−6.63
	500	−4.22	−1.17	+6.59	+4.86
	300	−0.80	+3.74	+0.51	+4.05
	200	−0.84	−10.01	+2.21	−2.38
	100	+0.05	+0.25	−1.12	−1.45
EREC	1000	—	—	—	—
	850	−0.53	+0.51	−7.96	−6.43
	700	−12.99	+1.82	−3.37	+2.04
	500	+3.41	−5.77	−1.34	−2.75
	300	+2.71	−1.57	−1.25	+4.45
	200	−12.56	−3.27	+2.09	+13.71
	100	+1.39	+0.29	+17.83	+7.64

In the middle (500-300 mb) and the lower (900-800 mb) tropospheres, the flux is mainly or close to positive (northward). Such type of distribution is found to be absent during the first week of polygon I. Figs. 8 (b & d) exhibit the existence of non-symmetry in the vertical distributions of the flux for both the weeks. It is also to note that the second weekly distribution in Fig. 8 (b) has significant similarity with those in Figs. 8 (a & c). In Figs. 9 (a & c) the distribution shows, in general, southward flux in the lower troposphere roughly between 1000 mb and 600 mb during second week. The general trend of the flux to be positive is observed in the middle troposphere (500-300 mb). But positive (northward) distribution exists from 950 mb to top of the troposphere during first week in polygon II. It can be seen from Figs. 9 (b & d) that the distributions of the eddy flux for both the weeks are negative (southward) in the lower troposphere, close to zero in the middle troposphere and positive (northward) in the upper troposphere. These overall distributional characteristics of eddy flux during the first week and second week in both the polygons can, perhaps, be attributed to the prevailing synoptic conditions during the study periods.

Distributions of meridional eddy flux of dry static and moist static energy covering the study periods for both the polygons have been shown latitudewise (at different longitudes) in Figs. 10 (a-d) and 11(a-d) respectively. In

Figs. 10 (a & b), showing ship positions roughly along the same latitude (6.3-7.0 N), it can be seen that the maximum southward flux at 700 mb gradually decreases with the advancement of monsoon. It is also interesting to observe that the flux beyond 500 mb upto about 200 mb level is always positive (northward). Figs. 10 (c & d) for positions roughly along the same latitudes (3.9-4.7 N) and (8.7-9.2 N) show that there is a tendency for the flux to be negative (southward) at 700 mb level and generally close to positive (northward) roughly between 400 mb and 150 mb levels. It is commonly observed in Figs. 10 (a-d) that the flux is minimum in the lowest troposphere (1000-800 mb). An examination of the Figs. 11 (a & b), showing meridional eddy flux distributions of moist static energy along roughly the same latitude (6.3-7.0 N), indicates the existence of positive (northward) flux broadly from middle to the top of the troposphere in polygon I whereas in polygon II the same is positive (northward) from 800 mb to about top of the troposphere. But at 700 mb level there exists the maximum negative flux (southward) in polygon I. This implies that there is a probable tendency for the flux to be positive (northward) below 500 mb level with the increasing longitudes to the east of 60° E and with the advancement of monsoon. From Fig. 11 (c), it can be seen that the eddy flux in polygon I is strongly negative (southward) having maximum at 700 mb across latitude 3.9 N from 850 mb to 450 mb levels, whereas the same is weakly negative (southward) or close to positive across 4.7 N within the layer between 700 mb and 300 mb. This again implies that the flux tends to be positive (northward) to the east of 60° E with the onset phase of monsoon. Some interesting deviation is observed in Fig. 11 (d) which shows distribution along the same but relatively higher latitude (8.7-9.2 N). In this case, the meridional eddy flux of moist static energy is negative (southward) between 1000 mb and 600 mb but positive (northward) from 600 mb onwards to the top of the middle troposphere in polygon I. But the flux in polygon II is strongly negative (southward) from 950 mb to about 600 mb having maximum at 850 mb and follows almost the same pattern and strength of that in polygon I between 600 mb and top of the middle troposphere. This, therefore, indicates that the meridional eddy flux of moist static energy is unlikely to the positive (northward) in the lower troposphere at higher latitudes to the east of 60° E even with the advancement of monsoon.

5. Conclusions

The study, presented in this paper, reveals the following tentative results :

(*a*) Eastward eddy flux of moist static energy becomes dominant during the onset phase of monsoon having maximum value within the layer 900-600 mb approaching minimum value between 600 mb and 400 mb levels.

(*b*) The well-marked magnitudinal difference between the zonal eddy fluxes of dry static and moist energy is mainly due to the contribution of eddy flux of latent heat energy which is related to the advancement of monsoon.

(*c*) The zonal eddy flux of dry static energy shows irregular distribution with height.

(*d*) Roughly along latitude 7.0 N to the east of 60° E, the maximum southward eddy flux of dry static energy at 700 mb tends to be northward with the increasing longitude as well as the advancement of monsoon.

(*e*) There exists positive (northward) or close to positive eddy flux of dry static energy roughly between 500 and 200 mb levels.

(*f*) The meridional eddy flux of dry static energy remains generally minimum in the lowest troposphere (1000-850 mb).

(*g*) The northward eddy flux of moist static energy in the upper troposphere extends to 700 mb or further downward along latitude 7.0 N and below to the east of 60° E with the advancement of monsoon.

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