

On the meridional and zonal fluxes of energy components in the troposphere over the Arabian Sea with the advancement of SW-monsoon

M. H. K. CHOWDHURY and S. KARMAKAR

Bangladesh Meteorological Department, Dacca

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ABSTRACT. The rawinsonde data of MONEX-79 have been utilized to study the zonal and meridional fluxes of dry and moist static energies and their weekly means for the troposphere over the Arabian Sea at lower latitudes. The mean zonal fluxes of dry and moist static energies, in general, show gradual march towards positive (eastward) value through the lower troposphere upto about 500 mb and the flux then becomes sharply negative (westward) from 300 mb onwards with the nearing of the on-setting date of monsoon. As the monsoon advances, the meridional fluxes of both dry static and moist static energy are found to have gradual change from the dominance of negative (southward) values towards positive in the lower and middle troposphere. The mean flux contribution of latent heat to that of moist static energy, both in the case of zonal and meridional, is not generally found to exceed 15 per cent of that of dry static energy in the lower troposphere. The latent heat contribution above 300 mb is insignificant.

1. Introduction

Chowdhury and Karmakar (1980) made a study on some aspects of energetics of the troposphere over the Arabian Sea with the advancement of southwest monsoon (hereinafter called monsoon only). In this paper the authors present their study on the meridional and zonal fluxes of energy components of the troposphere over the Arabian Sea in relation to the advancement of monsoon by utilizing the MONEX-79 data. The meridional and zonal fluxes of energy are important factors in maintaining general circulation of the atmosphere. Specially, such fluxes of energy over the Arabian Sea, which is the corridor of summer monsoon, may significantly influence the annual rainfall over the Indo-Bangladesh-Pakistan sub-continent (hereinafter called sub-continent only) and contribute in maintaining the summer circulation of the northern hemisphere. From the general circulation point of view the studies on fluxes of energy, both meridional and zonal have received attention of many scientists in the past (Palmen *et al.* 1958, Holopainen 1965, Hastenrath 1966).

But, only a few studies have been carried out on fluxes of energy and moisture in relation to monsoon (Anjaneyulu 1969, 1971; Ghosh *et al.* 1978). The purpose of the present study is to obtain quantitative estimates of the zonal and meridional fluxes of energy and to discuss their behaviour throughout the marine troposphere over the regional sea-basin, the Arabian Sea, with the advancement of monsoon. This could be useful in gaining insight into the monsoon dynamics and energetics which is one of the scientific aims of MONEX-79.

2. Basic considerations

The zonal fluxes of dry static energy (F_1) and moist static energy (F_2) may be written as:

$$F_1 = (c_p T + gz).u \quad (1)$$

$$F_2 = (c_p T + gz + Lq).u \quad (2)$$

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. The units

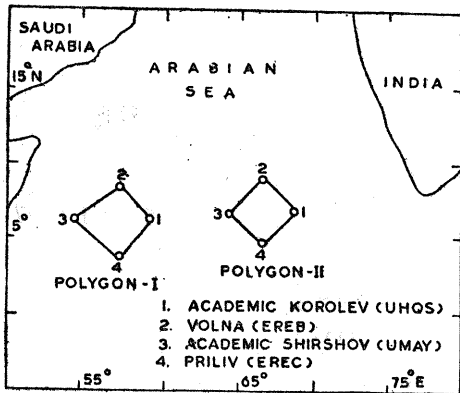
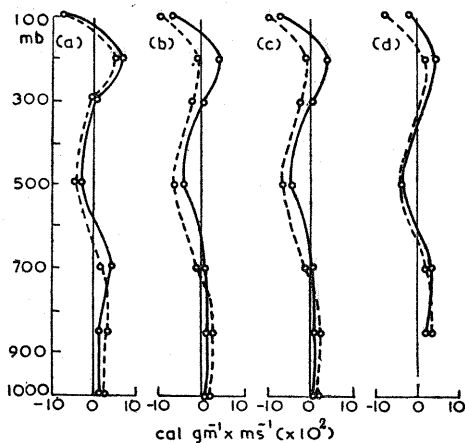


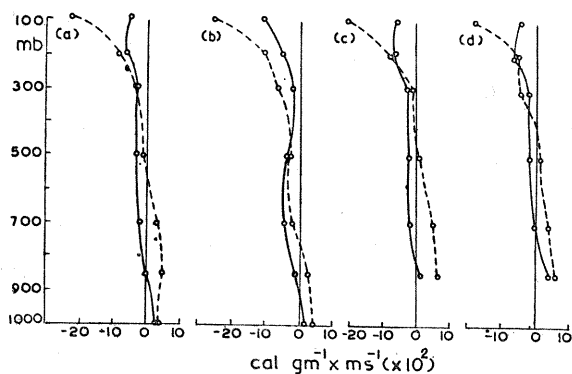
Fig. 1. Location of Monex ships



SHIPS: (a) UHQS (6.3°N, 59.1°E); (b) EREB (8.7°N, 57.0°E); (c) UMay (6.5°N, 54.5°E); (d) EREC (3.9°N, 57.1°E)

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Figs. 2 (a-d). Weekly mean zonal flux of dry static energy



SHIPS: (a) UHQS (6.8°N, 66.5°E); (b) EREB (9.2°N, 66.7°E); (c) UMay (7.0°N, 64.5°E); (d) EREC (4.7°N, 66.7°E)

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Figs. 3 (a-d). Weekly mean zonal flux of dry static energy

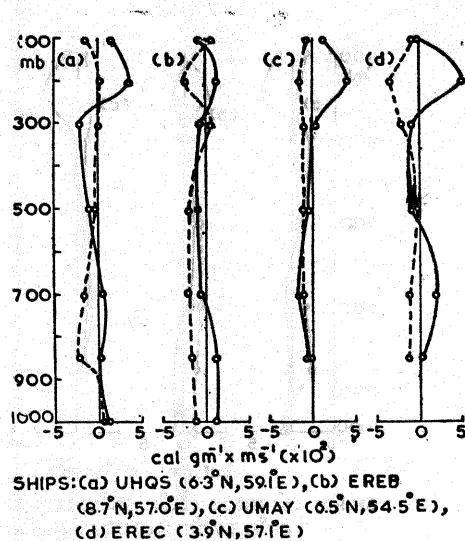
of F_1 and F_2 are $\text{cal gm}^{-1} \text{m sec}^{-1}$. The meridional fluxes of dry static and moist static energy can be obtained by replacing zonal wind component u by meridional wind component v in expressions (1) and (2).

3. Data source

A brief description about the source of data was given in the previous study (Chowdhury and Karmakar 1980). However, for a ready reference, the station location map is reproduced in Fig. 1. As in the previous study, all calculations are based on rawinsonde observations at standard isobaric levels from 1000 mb to 100 mb for 1200 GMT on board the ships forming polygons I and II during periods 16-29 May and 02-13 June 1979 respectively. Polygon I lies to the west of 60 deg. E meridian and polygon II to the east of it. Small data gaps in the observations, occurring on a few occasions, have been filled up by considering data of nearest synoptic hours. The errors introduced in the calculations of energy fluxes by this process are expected to be very small. The weekly mean values calculated in this study for polygon II covers 6 days, except in case of ship EREB where it is of 5 days; but for polygon I, these are 7-day means.

4. Results and discussions

4.1. Zonal flux of dry static energy — The dry static energy ($c_p T + gz$) and the zonal wind component u are calculated for polygons I and II. The zonal flux of dry static energy has then been evaluated for both the polygons using expression (1) for each day of the study periods in order to calculate the mean values. The profiles of weekly zonal flux are shown in Figs. 2 (a-d) and 3 (a-d) for polygons I and II respectively. It is found from the figures that the mean flux for each station position is positive (eastward) upto the level of about 650 mb with only one exception in case of ship EREB for polygon II during first week (02-07 June 1979). This exception was noted to be due to the absence of westerly current at 650 mb level for the latitudinal position of EREB and the absence can apparently be attributed to the non-existence of monsoon activity at that position. The profiles for polygon I represented by Figs. 2 (a-d) show gradual decrease of positive (eastward) value roughly between 850 mb and 700 mb in case of second weekly mean, whereas in case of first weekly mean the flux increases from 850 mb to 700 mb first and then decreases upto about 650 mb. Both the profiles then show maximum negative (westward) and positive (eastward) fluxes at 500 mb and 200 mb respectively having zero value roughly near 300 mb

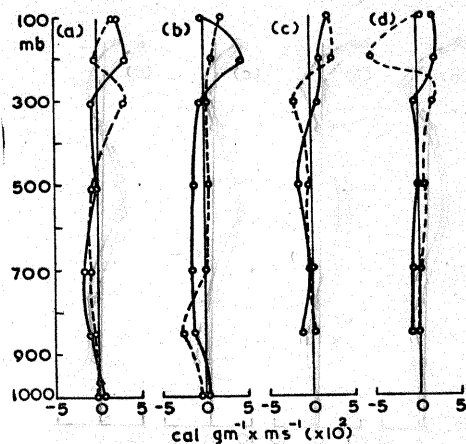


Figs. 4 (a-d). Weekly mean meridional flux of dry static energy

and 150 mb levels. It is interesting to observe that the zonal mean flux for polygon II, shown in Figs. 3 (a-d) during the first week, becomes generally negative within the layer between 850 mb and 700 mb, and then remains so upto the top of the troposphere (100 mb level), whereas the same for the second week is generally positive upto about 500 mb level with only one exception for EREB. This positive zonal flux indicates the dominance of westerly flow from the surface upto 500 mb level with the advancement of monsoon. Figs. 3 (a-d) show the reversal of the flux profiles wherein the profile for second week is more negative (westward) than that of the first week from top of the middle troposphere signifying the establishment of easterly jet with the nearing of the date of onset of monsoon. The same trend, though relatively weak is observable in Figs. 2 (a-d) from first week to the second week for polygon I, roughly from 650 mb onwards.

4.2. Meridional flux of dry static energy —

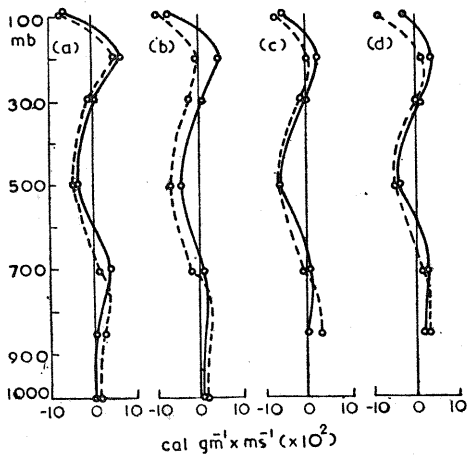
To find out the meridional flux of dry static energy, the components $(c_p T + gz)$ and v (the meridional wind component) have been multiplied together for each day of the study periods. The profiles for weekly mean meridional flux are shown in Figs. 4 (a-d) and 5 (a-d) representing polygons I and II respectively. It is found from the figures that mean meridional flux of dry static energy approaches a broad minimum value roughly between 600 mb and 350 mb levels, while it reaches significant maxima both in the uppermost and lower troposphere. It is also important to observe from Figs. 4 (a-d) that the second weekly mean flux is generally



Figs. 5 (a-d). Weekly mean meridional flux of dry static energy

negative (southward) through the troposphere upto 350 mb level. Whereas, in the case of first week existence of positive flux (northward) across equator is observed in the lower troposphere. This anomalous behaviour of weekly meridional flux can be attributed to the delaying of the onset of monsoon. In case of polygon II as shown in Figs. 5 (a-d), the mean flux for first week is roughly negative (southward) through all the layers upto the top of the middle troposphere, whereas the negative flux (southward) for the second week is less dominant in the layer 1000 mb to 500 mb except in case of ship EREB. This gradual weakening of the dominance of southward flux in the lower and middle troposphere implies the advancement of the date of onset of monsoon.

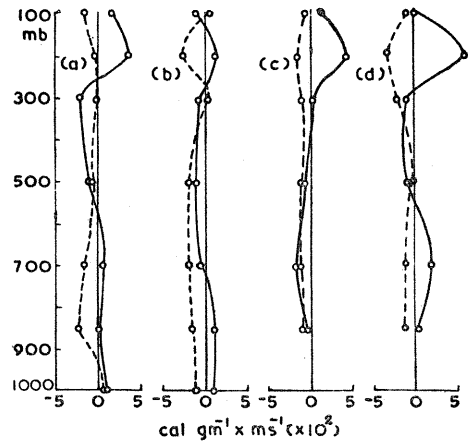
4.3. Zonal flux of moist static energy — The weekly mean zonal moist static energy fluxes as per expression (2) are shown in Figs. 6 (a-d) and 7 (a-d) for polygons I and II respectively. Their distribution is very similar for the dry static energy flux distribution indicated in Figs. 2 and 3. As in the Figs. 6 (a-d) the mean flux is positive (eastward) from 1000 mb to about 650 mb whereas the same in Figs. 7 (a-d) during first week extends upto about 750 mb level and during the second week roughly to the level of 450 mb except for ship EREB where it is upto about 750 mb only. During both the weeks the Figs. 6 (a-d) show gradual decrease of positive (eastward) values and attainment of negative (westward) values roughly between 600 mb and 300 mb levels reaching maxima at 500 mb level. The profiles again show positive (eastward) flux between 300 mb and 150 mb levels with maxima



SHIPS: (a) UMQS (6.3°N, 59.1°E); (b) EREB (8.7°N, 57.0°E); (c) UMAX (6.5°N, 54.5°E); (d) EREC (3.9°N, 57.1°E)

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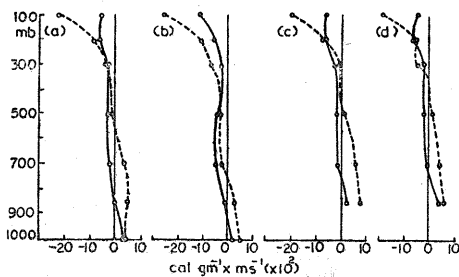
Figs. 6 (a-d). Weekly mean zonal flux of moist static energy



SHIPS: (a) UHQS (6.3°N, 59.1°E); (b) EREB (8.7°N, 57.0°E); (c) UMAX (6.5°N, 54.5°E); (d) EREC (3.9°N, 57.1°E)

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

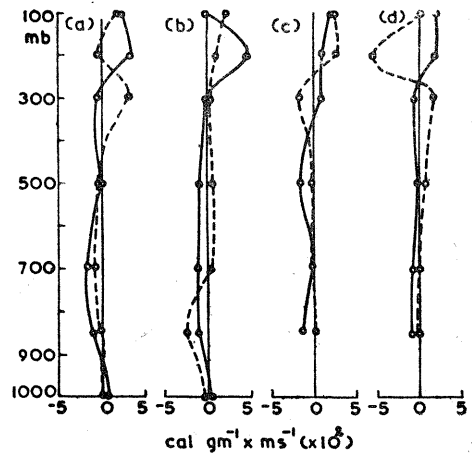


SHIPS: (a) UMQS (6.8°N, 68.9°E); (b) EREB (9.2°N, 66.7°E); (c) UMAX (7.0°N, 64.5°E); (d) EREC (4.7°N, 66.7°E)

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Note — In Figs. 6 & 7 ship at (a) is UHQS instead of UMQS

Figs. 7 (a-d). Weekly mean zonal flux of moist static energy



SHIPS: (a) UHQS (6.8°N, 68.9°E); (b) EREB (9.2°N, 66.7°E); (c) UMAX (7.0°N, 64.5°E); (d) EREC (4.7°N, 66.7°E)

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

at 200 mb. From 150 mb onwards the mean fluxes sharply become negative (westward). In comparison with the Figs. 6 (a-d) there is marked difference in Figs. 7 (a-d) where during both the weeks no maxima of negative (westward) value are observed at 500 mb level. The profiles instead show clear march toward positive (eastward) value in Figs. 7 (a-d) and become generally positive upto about 450 mb level as stated earlier. This gradual change over to positive value is due to the contribution of latent heat flux which is not more than 15 per cent of the mean dry static energy flux in the lower troposphere. It is important to observe, during both the weeks here, that the sharp increase of negative (westward) values start from about 300 mb level onwards with more sharp increase during the second week than that during first week which indicate the intensification of easterly jet during this period. The gradual attainment of positive (eastward) values of the mean fluxes in the lower and middle troposphere, and the sharp increase in the negative (westward) values beyond 300 mb level from first week to the second week signify the nearing of the date of onset of monsoon.

4.4. Meridional flux of moist static energy—

The vertical distribution of the weekly mean meridional fluxes of moist static energy for polygons I and II are shown in Figs. 8 (a-d) and 9 (a-d). These vertical distributions display more or less the same behaviour as in meridional flux of dry static energy with a variation of not more than 15 per cent of energy flux in the lower troposphere, and decreasing with height. Beyond 300 mb the contribution from latent heat flux is insignificant.

5. Conclusions

From the study the following results can be inferred:

(i) Zonal positive fluxes (eastward) of dry and moist static energies generally exist in the lower troposphere upto the level of about 650 mb at lower latitudes over the Arabian Sea. Maximum negative (westward) and positive (eastward) fluxes exist at 500 mb and 200 mb

levels respectively when the date of onset of monsoon is not near.

(ii) With the advancement of monsoon, the mean zonal fluxes of dry and moist static energies, in general, show gradual march towards positive (eastward) value through the lower troposphere upto about 500 mb and attainment of pronounced negative (westward) value from the top of the middle troposphere, signifying the dominance of westerly flow in the lower troposphere and the easterly flow in the upper troposphere respectively.

(iii) The trend of sharp increase in negative (westward) value of mean zonal dry and moist static energies fluxes are observed to be predominant from about 300 mb upwards with the advancement of monsoon implying the setting of easterly jet in the upper troposphere at lower latitudes.

(iv) The gradual change of the mean meridional fluxes of both dry static and moist static energy from the dominance of negative (southward) values toward positive (northward) in the middle troposphere is observed with the advancement of monsoon.

(v) Mean flux contribution of latent heat to that of moist static energy, both in the case of zonal and meridional, is not generally found to exceed 15 per cent of that of dry static energy in the lower troposphere over the Arabian Sea at lower latitudes. The contribution of latent heat beyond 300 mb becomes insignificant.

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