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Inter-seasonal and inter-annual variations of mean and eddy atmospheric energetics over India

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सार — 1983 से 1987 तक की अवधि के दौरान 20 केन्द्रों के 1000 हे० पा० से 250 हे० पा० तक के दैनिक उपरितन वायु आंकड़ों का उपयोग करते हुए भारत के ऊर्ध्वाधर समेकित माध्य एवं भंवर संवेद्य और गुप्त ऊष्मा फ्लक्स की अन्तरमौसमी और अन्तवार्षिक विविधताओं की जांच की गई। ऊर्ध्वाधरीय समेकित अनुरेखांश संवेद्य एवं गुप्त फ्लक्स (माध्य एवं भंवर) उत्तर पूर्वी भागों को छोड़कर देश के अन्य स्थानों में सामान्यत: दक्षिणाभिमुखी थे। हेडले परिसंचरण के मौसमी विचलनों के साथ-साथ माध्य संवेद्य ऊष्मा और गुप्त ऊष्मा फ्लक्स के मानों में बड़े पैमाने पर मौसमी परिवर्तन होता है। भारत के उत्तरी भागों में वर्षा ऋतु के पहले अधिकतम संवेद्य ऊष्मा फ्लक्स का पता चला है। वर्षा ऋतु के दौरान मध्य भारत में अधिकतम गुप्त ऊष्मा फ्लक्स का पता चला है। सभी ऋतुओं में माध्य प्रवाह के कारण फ्लक्स की तुलना में भंवर फ्लक्स दो श्रेणी कम थे। शीत ऋतु में अधिकतम भंवर फ्लक्स होते हैं और ये बड़े पैमाने पर क्षणिक भंवर से प्रतिपादित होते हैं। 15° उत्तर को भूमध्यरेखा की ओर भंवर फ्लक्स व्यावहारिक रूप से महत्वहीन थे। यद्यपि निम्न अक्षांशों में फ्लक्स की मौसमी विविधताएं ऊर्ट (1971) द्वारा प्राप्त वार्षिक चक्र की क्षेत्रीय अभिरचना से भिन्न थी।

1983 (अच्छी वर्षा का वर्ष) और 1987 (खराब वर्षा का वर्ष) के बीच अनुरेखांश माध्य और भंवर फ्लक्स के मानों में उल्लेखनीय भिन्नताएं थीं। मानसून पूर्व तथा मानसून के दौरान 1983 (1987) में क्षणिक भंवर के कारण संवेद्य ऊष्मा फ्लक्स के मान भूमध्यरेखाभिमुखी (ध्रुवाभिमुखी) थे। इसी तरह से 1983 में वर्षा ऋतु के दौरान बड़े पैमाने पर उत्तराभिमुख माध्य संवेद्य तथा गुप्त ऊष्मा फ्लक्स पाए गए थे। इसके अतिरिक्त 1983 से 1987 के मध्य भी क्षेत्रीय संवेद्य तथा गुप्त ऊष्मा फ्लक्स की ऊर्ध्वाधर संरचना में उल्लेखनीय विभिन्नताएं थीं।

ABSTRACT. Using daily upper air data from 1000 to 250 hPa of 20 stations during the period 1983-87, the inter-seasonal and inter-annual variations of vertically integrated mean and eddy sensible and latent heat fluxes over India were examined. Vertically integrated meridional, sensible and latent fluxes (both mean and eddy fluxes) were generally southwards over the country except over northeastern parts. Large seasonal variation of mean sensible heat and latent heat flux values occur in association with the seasonal shifts of Hadley circulation. Maximum sensible heat fluxes were observed during pre-monsoon season over northern parts of India. Maximum latent heat fluxes were observed over central parts of India during monsoon season. Eddy fluxes were two order smaller than fluxes due to mean flow during all seasons. Maximum eddy fluxes occur in winter and are accomplished by large scale transient eddies. The eddy fluxes were practically negligible equatorwards of 15°N. Seasonal variations of fluxes over low latitudes were, however, different from the zonal pattern of annual cycle obtained by Oort (1971).

There were significant differences in meridional mean and eddy flux values between 1983 (a good monsoon year) and 1987 (a bad monsoon year). During 1983 (1987) the sensible heat flux values due to transient eddies were equatorwards (polewards) during the premonsoon as well as monsoon seasons. Similarly during monsoon season of 1983 larger northward mean sensible and latent heat fluxes were observed. In addition there were significant differences in vertical structure of zonal sensible and latent heat fluxes between 1983 and 1987 also.

Key words — Eddy, Energetics, Flux, Sensible heat, Latent heat, Meridional, Monsoon.

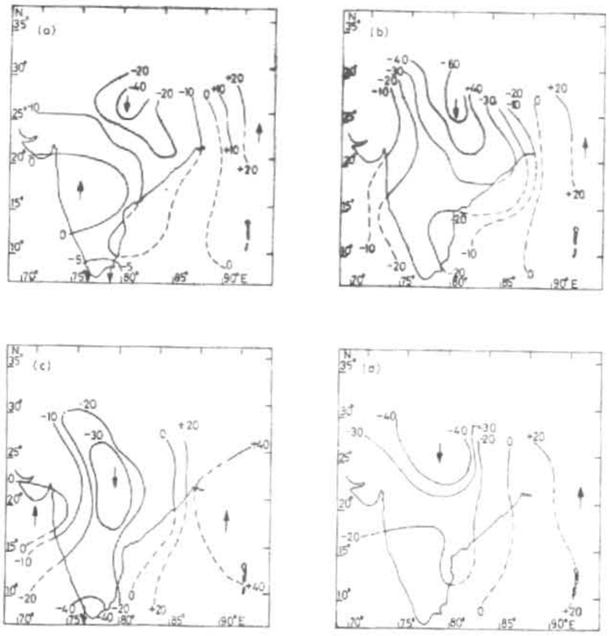
1. Introduction

There had been numerous studies on evaluation of atmospheric fluxes of energy, momentum and moisture in the zonally averaged scheme. The most comprehensive documentations of these statistics are those of Oort and Rasmusson (1971), Oort (1971) and Newell *et al.* (1974).

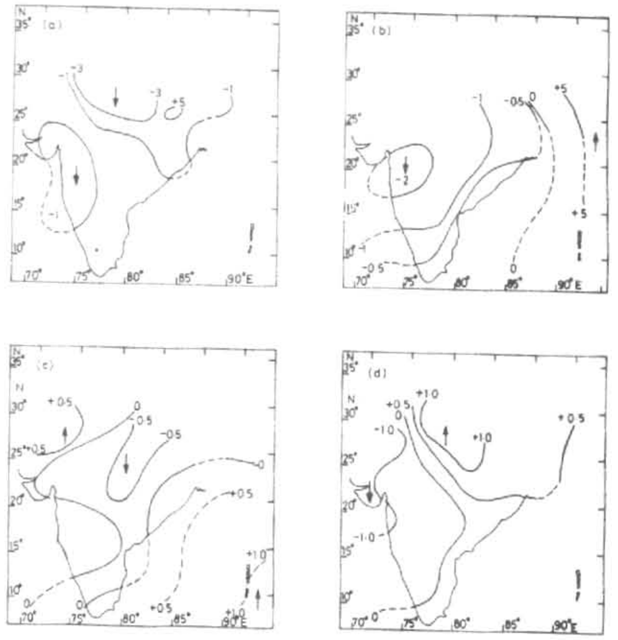
Subsequently, efforts have been put into the evaluation of atmospheric statistics for smaller scales by Blackmon (1976) and Lau (1978). This approach is essential because local atmospheric conditions may differ considerably from the zonal average. Following this approach Alestalo and Holopainen (1980) studied atmospheric energy fluxes over Europe.

Appa Rao (1981) studied atmospheric energetics over India during monsoon season using daily aerological data of 1966 and 1967 of 11 stations. He used data upto 650 hPa level only.

This study, is designed to examine the inter-seasonal and interannual variations of vertically integrated mean and eddy sensible and latent heat



Figs. 1 (a-d). Meridional sensible heat flux (10^6 W/m) due to mean flow for (a) Winter (b) Pre-monsoon (c) Monsoon and (d) Post-monsoon seasons



Figs. 2 (a-d). Meridional sensible heat flux (10^6 W/m) due to eddy flow for (a) Winter (b) Pre-monsoon (c) Monsoon and (d) Post-monsoon seasons

fluxes over India using a larger data set, *i.e.*, with data of more number of years, layers and stations.

2. Data

The daily upper air data from 1000 to 250 hPa, steps of 50 hPa for 0000 UTC of 20 stations were used for this study. The period considered for the study was 1983-87. Surface level was omitted in order to avoid radiation and topographical effects. The stations considered in this study are Thiruvananthapuram, Minicoy, Port Blair, Mangalore, Madras, Goa, Hyderabad, Visakhapatnam, Bombay, Bhubaneshwar, Ahmedabad, Nagpur, Calcutta, Guwahati, Dibrugarh, Jodhpur, Bhopal, Lucknow, Patna and New Delhi.

3. Method of study

The vertically integrated sensible heat flux is computed as,

$$F_{SH} = \frac{C_P}{g} \int_{P_1}^{P_2} \overline{VT}\, dP \quad \text{watts/m} \qquad (1)$$

between the layers P_1 and P_2. We have integrated the flux between 950 and 250 hPa levels.

The flux can be split into mean and transient eddy components,

$$F_{SH} = \frac{C_P}{g} \int_{P_1}^{P_2} (\overline{V}\overline{T} + \overline{V'T'})\, dP \quad \text{watts/m} \qquad (2)$$

Similarly, the vertically integrated mean and eddy latent heat fluxes are computed as,

$$F_{LH} = \frac{L}{g} \int_{P_1}^{P_2} (\overline{V}\overline{q} + \overline{V'q'})\, dp \quad \text{watts/m} \qquad (3)$$

The basic data consists of daily station values of the meteorological parameters *u, v, T* and *q* where *u* and *v* are zonal and meridional wind components, *T* is temperature and *q* is specific humidity. The daily data of each station were first used to compute monthly mean statistics at all levels between 950 and 250 hPa. The quantities $\overline{u}$, $\overline{v}$, $\overline{T}$, $\overline{q}$, $\sigma(u)$, $\sigma(v)$, $\sigma(T)$, $\sigma(q)$ were computed. The standard deviations were used as a check for gross errors in the data. This procedure rejected observations differing from the mean by more than 3σ.

Long term seasonal mean values were calculated from the monthly mean statistics for winter (December to February), premonsoon (March to May), monsoon (June to September) and post-monsoon (October to November) seasons. If $\overline{u}_m$ and $\overline{N}_m$ are the values of the monthly means and number of data points entering the respective means for all months for all years in a typical season, the resultant long-term seasonal mean is simply,

$$\bar{u} = \frac{\sum_m \bar{N}_m \bar{u}_m}{\sum \bar{N}_m} \qquad (4)$$

and similarly for the other terms.

Time departures are obtained from the daily values and used for calculation of eddy terms.

Mean and eddy terms were, then, calculated at each level and were later integrated vertically.

Seasonal energy fluxes were calculated yearwise also to examine the interannual variations. During the period considered in the study, *i.e.,* 1983-87, 1983 was a good monsoon year with excess rainfall and 1987 was a drought year with deficient rainfall. These two typical years were considered for examination of interannual variations. Individual fluxes for lower layer (950-750 hPa), middle layer (750-500 hPa) and upper layer (500-250 hPa) were also analysed for each season and results are discussed.

4. Results

4.1. *Seasonal variations*

Figs. 1 (a-d) show meridional components of sensible heat fluxes due to mean flow during winter, pre-monsoon, monsoon and post-monsoon seasons respectively.

It can be noticed in general, the fluxes are mainly southwards except over eastern parts of India and some portions of western India. Fluxes were higher over northern parts of India during winter, pre-monsoon and post-monsoon seasons with a higher value during the post-monsoon season. During monsoon season maximum southward flux values occur over central and extreme southwestern parts of the country.

Large seasonal variations occur since the mean meridional flow of sensible heat tends to be from the winter in to summer hemisphere associated with the shifts in Hadley circulations. Northern Hemisphere (NH) Hadley cell transports sensible heat and latent heat fluxes southwards. The northward heat flux over eastern parts of India are, however, in accordance with the meridional circulations over that area (Rao 1961). During monsoon season large southward heat fluxes were observed over southern parts of India. These are due to deep layer of northerlies commencing almost from the surface closer to the equator observed during monsoon season (Rao 1961). In general, the seasonal variations resembled the meridional wind flow pattern obtained by Rao (1961).

In case of individual layers the patterns of sensible heat fluxes are almost simiiar to that of integrated zone during all seasons except during monsoon season. During monsoon season, over northern latitudes, southward fluxes were observed only in lower and middle layers, whereas, northward fluxes were observed in the upper layer. In the lower latitudes the integrated southward fluxes were mainly due to contributions from lower layer and were responsible for the interseasonal variations also.

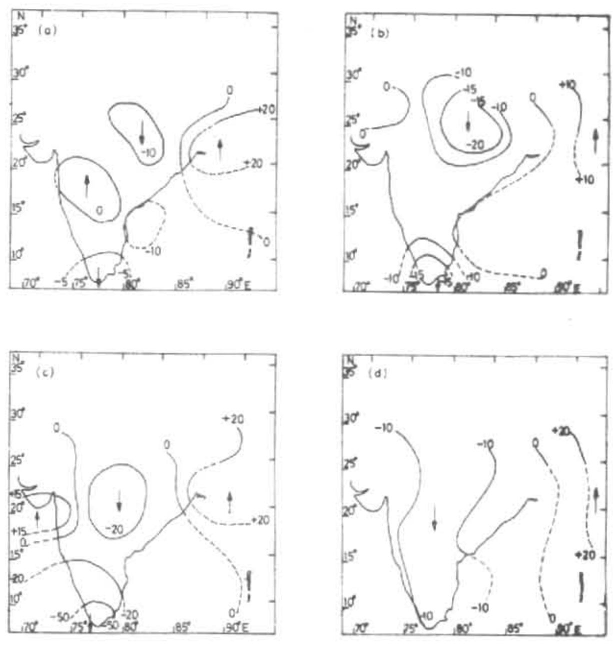
Figs. 2 (a-d) show meridional components of sensible heat fluxes due to eddy flow during winter, pre-monsoon, monsoon and post-monsoon seasons respectively.

Eddy fluxes were two order lower than mean fluxes during all seasons. Like mean fluxes, eddy fluxes were also northerly over major parts of the country except during post-monsoon season. During post-monsoon season the eddy fluxes were northerly only over western and central parts of India. Northerly eddy fluxes were highest over northern parts of India during winter season. This maximum flux of sensible heat is accomplished by large scale transient waves. This observation is different from the results for higher latitudes where the flux showed a pronounced poleward maximum in winter. The transient energy fluxes were practically negligible equatorwards of 15°N Lat. because of horizontal homogeniety of temperature and humidity.

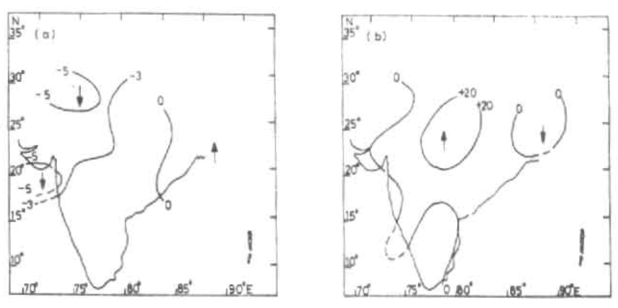
During winter, contribution to integrated maximum eddy sensible heat fluxes was generally due to middle and upper layers. During post-monsoon season over northern latitudes, the integrated poleward fluxes were mainly due to upper layers.

Figs. 3 (a-d) are meridional latent heat fluxes due to mean flow during winter, pre-monsoon, monsoon and post-monsoon seasons. respectively.

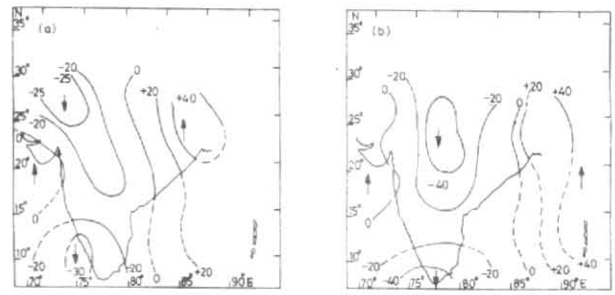
Latent heat fluxes were one order less than sensible heat fluxes. The fluxes were generally southwards except over northeastern parts of India similar to pattern of sensible heat fluxes. The seasonal variation was similar to that of sensible



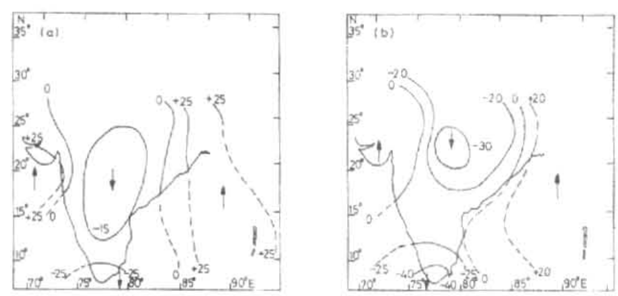
Figs. 3 (a-d). Meridional latent heat flux (10^6 W/m) due to mean flow for (a) Winter (b) Pre-monsoon (c) Monsoon and (d) Post-monsoon seasons



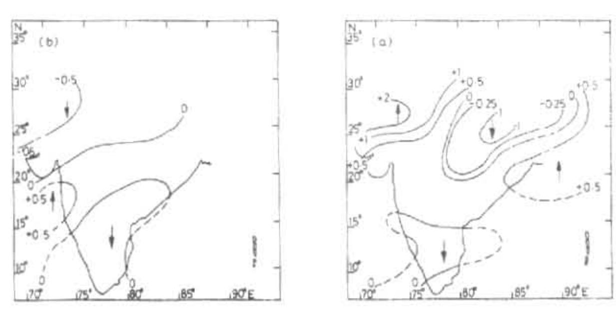
Figs. 4. (a &b). Meridional sensible heat flux (10^6 W/m) anomaly due to eddy flow during pre-monsoon season of (a) 1983 and (b) 1987



Figs. 5 (a & b). Meridional sensible heat flux (10^6 W/m) due to mean flow during monsoon season of (a) 1983 and (b) 1987



Figs. 6 (a & b).. Meridional latent heat flux (10^6 W/m) due to eddy flow during monsoon season of (a) 1983 and (b) 1987



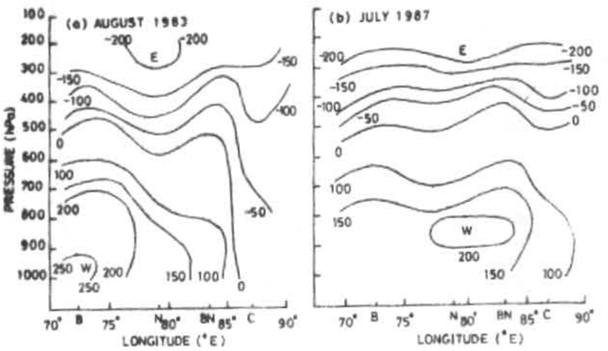
Figs. 7 (a & b). Meridional sensible heat flux (10^6 W/m) due to eddy flow during monsoon season of (a) 1983 and (b) 1987

heat fluxes. Maximum latent heat fluxes were observed during summer monsoon season over central parts of India and southwestern parts of India. During all seasons latent heat fluxes were northwards over Head Bay and northeastern parts of India.

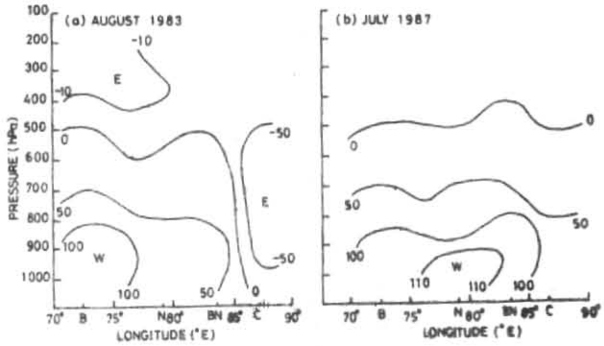
The patterns of sensible heat fluxes in case of individual layers were almost similar to that of integrated zone during all seasons. But the maximum contributions were from the lower layer and were responsible for the inter-seasonal variations also.

Oort (1971), who examined the annual cycle of the zonally-averaged meridional transport of atmospheric energy, found that at low latitudes in summer there is a weak northward flow of sensible and latent heat fluxes while the flow is predominantly southwards during the rest of year. However, over low latitudes of Indian region heat fluxes were southwards throughout the year.

Appa Rao (1981) analysed fluxes for two years and they also found similar results in respect of monsoon season, *i.e.,* southward sensible and latent heat fluxes over most parts of India. However, they integrated only upto 650 hPa. Parker (1970) obtained that during June at 30°N Lat. the flux of sensible heat by mean is southwards and greater compared to eddies, whereas, flux of latent heat by eddies is higher and northward compared to mean.



Figs. 8 (a & b). Vertical profile of zonal sensible heat flux (10^{-1} ms^{-1} K) during (a) August 1983 (b) July 1987



Figs. 9 (a & b). Vertical profile of zonal latent heat flux (10^{-1} ms^{-1} K) during (a) August 1983 and (b) July 1987

4.2. *Energetics during two contrasting years 1983 and 1987*

4.2.1. *Pre-monsoon season*

It has been found that between 1983 and 1987, there were no significant differences in sensible and latent heat fluxes due to mean flow. However, there were significant differences in sensible heat fluxes due to eddy flow as indicated in Figs. 4 (a & b) which show the anomalies of meridional sensible heat fluxes during pre-monsoon season of 1983 and 1987 respectively. It can be seen that during 1983, the eddy fluxes were generally southward over most parts of the country, whereas during 1987 the eddy fluxes were generally northwards. Thus, during 1987 more than normal heat was transported from tropics to mid-latitudes across sub tropical regions. However, more case studies are to be carried out, to understand the nature of interannual variability in relation to performance of the summer monsoon over India.

The southward (northward) eddy sensible heat flux over northern latitudes during pre-monsoon of 1983 (1987) were mainly due to the contribution from upper layer.

4.2.2. *Monsoon season*

Figs. 5 (a & b) show meridional sensible heat flux due to mean flow during monsoon season of 1983 and 1987 respectively. It can be noticed that flux values were higher during 1983 except over eastern parts of India and northwest India. During 1983, there was a cent percent increase in northward flux values over the Head Bay area.

Figs. 6 (a & b) show meridional latent heat flux due to mean flow during monsoon season of 1983 and 1987 respectively. The pattern of flux values during 1983 and 1987 were similar, however, the northward fluxes were higher during 1983 especially over Head Bay and northwest India mainly due the contribution from lower layer.

Figs. 7 (a & b) show meridional sensible heat flux due to eddy flow during 1983 and 1987 respec tively. The significant difference between these two years were noticed over northwest India. Over northwest India fluxes were southwards during 1983, whereas, the fluxes were northwards during 1987. This northward transport of sensible heat fluxes during drought years were reported by Asnani & Awade (1978), and Sikka & Gadgil (1978). Such northward sensible heat flux during 1987 were perceptible during pre-monsoon season also.

Thus, it has been found that there were significant differences in flux values, both in magnitude and direction due to mean and eddy flows during pre-monsoon and monsoon seasons of 1983 and 1987.

4.3. *Vertical structure of sensible and latent energy fluxes during 1983 and 1987*

Vertical structure of sensible and latent heat fluxes during 1983 and 1987 were examined by constructing longitudinal cross sections of the fluxes.

Figs. 8 (a & b) show longitudinal cross section of vertical variations of zonal sensible heat flux ($\overline{uT}$) along 20°N during August 1983 and July 1987 respectively. During August 1983 (July 1987) monsoon was active (weak) with excess (deficient) rainfall.

During August 1983, there was a convergence of sensible heat fluxes around 85°E, in the lower levels due to strong westerly heat flux on west and easterly heat fluxes on east of 85°E. On the other hand during July 1987, there was altogether westerly fluxes through the width of country and there was divergence of sensible heat fluxes over central parts of India. During July 1987, however, stronger easterly upper tropospheric flux values were observed.

Figs. 9 (a & b) show the longitudinal cross sections of vertical structure of zonal vapour fluxes ($\overline{uq}$) during August 1983 and July 1987 respectively. Similar to sensible heat fluxes, there was strong convergence of vapour fluxes during August 1983 around 85°E in the lower troposphere whereas during July 1987 there was vapour flux divergence over central parts of India in the lower troposphere.

These differences in structure of flux values are due to different circulation patterns which prevailed during August 1983 and July 1987. Convergence of zonal vapour flux in 1983 compared to the divergence in 1987 tie well in relation to the performance of monsoon rains in the two years.

5. Conclusions

The following conclusions can be drawn from this study :

(*i*) Vertically integrated meridional, sensible and latent heat flux values were generally southwards over the country in all seasons except over northeastern parts where the northward fluxes were observed. Maximum sensible heat fluxes were observed during pre-monsoon season over northern parts of India and maximum latent heat fluxes were found over central parts of India during monsoon season. Large seasonal variations occur in association with the seasonal shifts of Hadley circulation and resembled meridional wind patterns over Indian region. However, seasonal variation of fluxes over low latitudes were different from the zonal pattern obtained from Oort (1971).

(*ii*) Eddy fluxes were one to two order lower than fluxes due to mean flow during all seasons. Similar to the fluxes due to mean flow, eddy fluxes were also mainly southwards over most parts of the country. The eddy fluxes were maximum in winter over northern latitudes and were practically negligible over low latitudes.

(*iii*) During monsoon seasons of 1983 (1987) sensible heat fluxes due to transient eddies were equatorwards (polewards) and these differences were perceptible during pre-monsoon season also. Northward mean fluxes were larger over Head Bay area and western parts of India during 1983.

(*iv*) During 1983 the moisture flux showed convergence over India compared to divergence in 1987 which go well with the performance of monsoon during two years.

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