On the Meridional Local Eddy Flux of Heat over India

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ABSTRACT

Computations for the northward local eddy flux of heat are presented for twelve Indian stations, for a period of one year. Over India the local eddy flux term appears to contribute little towards the total flux required by the hemispheric radiative imbalance. The seasonal changes of the local eddy flux of latent heat are related to the monsoon pattern.

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1. Method of computation

Following Priestley (1949), let Q represent the time averaged total northward heat flux per unit time accomplished by the atmosphere at any station:

$$Q=\frac{C_p}{g}\int_0^{p_0}\overline{VT}\,dp+\frac{L}{g}\int_0^{p_0}\overline{VX}\,dp, \qquad (1)$$

where the bar denotes a time average, C_p = specific heat at constant pressure, g = acceleration due to gravity, V = meridional component of horizontal wind vector, T = temperature in deg K, p_0 = pressure at the earth's surface, L = latent heat of vaporization, and X = humidity mixing ratio. The first term on the right hand side of (1) represents sensible heat flux while the second represents latent heat flux.

Now in the usual manner if we look upon the variables V, T, and X as compounded of their respective time means $\bar{V}$, $\bar{T}$, and $\bar{X}$ and their respective deviations V', T', and X' from these time means, we can write (1) in the form,

$$Q=\frac{C_p}{g}\int_0^{p_0}\bar{V}\bar{T}\,dp+\frac{L}{g}\int_0^{p_0}\bar{V}\bar{X}\,dp+\frac{C_p}{g}\int_0^{p_0}\overline{V'T'}\,dp+\frac{L}{g}\int_0^{p_0}\overline{V'X'}\,dp. \qquad (2)$$

The first two terms on the right hand side of (2) measure the effect of the mean meridional circulation and the standing eddies while the last two terms measure the local eddy flux. Attention is focused on the last two terms in the present study.

2. Data and analysis

At first, computations were carried out for four Indian stations; Delhi (28°39′N, 79°17′E), Calcutta (23°36′N, 88°23′E), Nagpur (21°8′N, 79°5′E) and Bombay (18°55′N, 72°50′E) for the period of September 1954 to August 1955, since radar wind data were available only at these stations at that time. Later, after the introduction of rawin at most of the radiosonde stations of India, the local eddy flux was calculated for twelve stations, Delhi, Guahati (26°35′N, 73°1′E), Allahabad (25°24′N, 81°51′E), Jodhpur (26°15′N, 73°1′E), Calcutta, Nagpur, Veeraval (25°54′N, 70°23′E), Bombay, Visakhapatnam (17°42′N, 83°19′E), Madras (13°4′N, 80°14′E), Port Blair (11°40′N, 92°46′E) and Trivandrum (8°29′N, 76°57′E), for the year December 1956 to November 1957. Throughout the investigation, observations reported only from these stations at 8:30 p.m. Indian Standard Time (IST) were used. At Visakhapatnam only, where rawin was not installed, the 5:30 p.m. IST pibal wind data were utilized. The soundings at these stations are taken on a synoptic basis daily by standard methods. Incidentally, these data are better than those available to Peixoto (1958, 1960) at low latitudes, for his far more extensive hemispheric studies.

At the 300-mb level, the highest level studied here, data were available for nearly 70 per cent of the time of study at almost all the rawin stations, whereas for levels below the 300-mb level, the data were comparatively superior. This might introduce a selectivity towards lower winds at high levels due to the disappearance of the balloon in stormy wind conditions. Thus these results must be taken only as indicative but not conclusive. Levels above the 300-mb level were not studied because of the relative sparseness of the data. The year was divided into four seasons appropriate for this region: winter (December–February), summer (March–May), monsoon (June–September), and post-monsoon (October–November).

3. Discussion of the results

In Fig. 1 the mean annual sensible heat flux is plotted against the pressure level for all the stations considered.

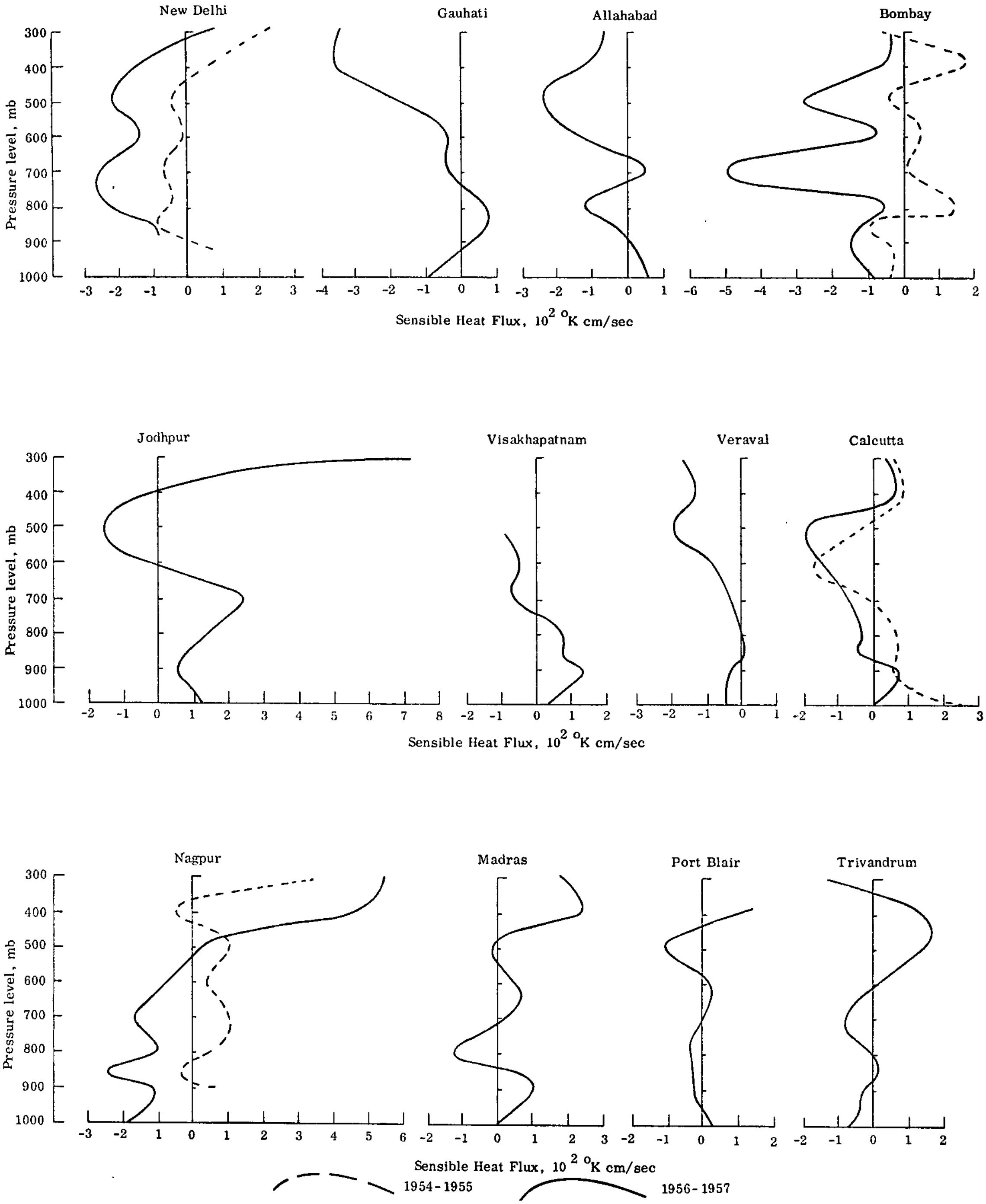

FIG. 1. Vertical variation of sensible heat flux.

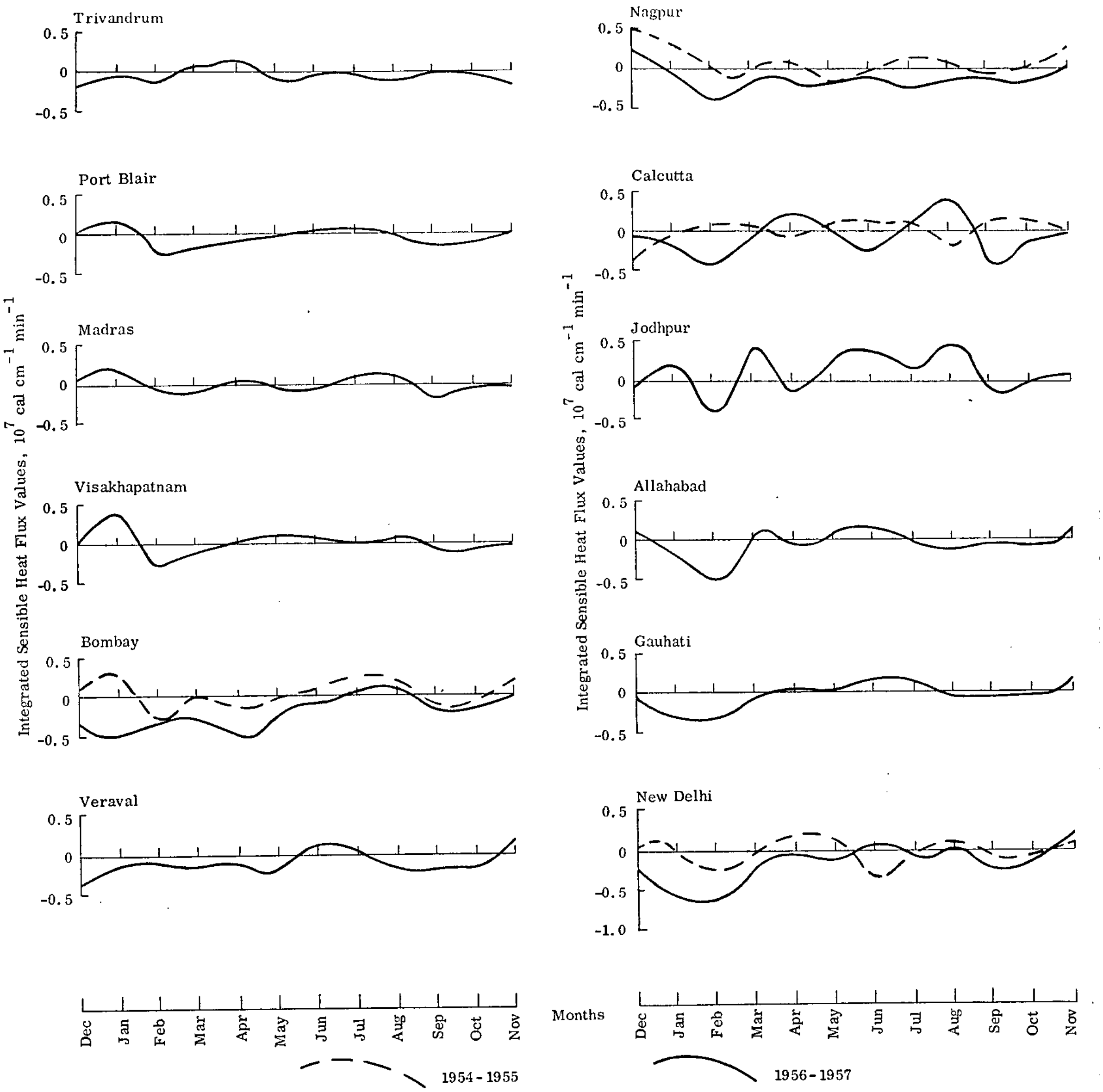

FIG. 2. Monthly variation of integrated sensible heat flux.

It can be observed from these figures that at all stations the flux values are very small in the lower levels and show maximum values either in the middle or upper troposphere. This is in striking contrast with the results of Priestley (1940), Nyberg and Schmacke (1951), White (1951), and Peixoto (1960), which showed considerably higher values in the lower troposphere decreasing generally with altitude up to the upper troposphere. The comparative absence in the tropics of frontal-type disturbances, which produce the strong temperature fluctuations in the lower levels of middle latitudes, may be the reason for this behavior. The high flux values in the upper levels suggest an increase in the eddy activity at those levels over this region.

In Fig. 2 the monthly variation of vertically-integrated sensible heat flux for all 12 stations is given. It can be seen that, in general, the flux is a maximum equatorwards in winter. This observation is different from the results of the earlier workers for higher latitudes where the flux showed a pronounced *poleward* maximum in winter. These strong negative flux values are probably related to the "subsiding northerlies," a feature of India's winter characterized by clear skies and fair weather.

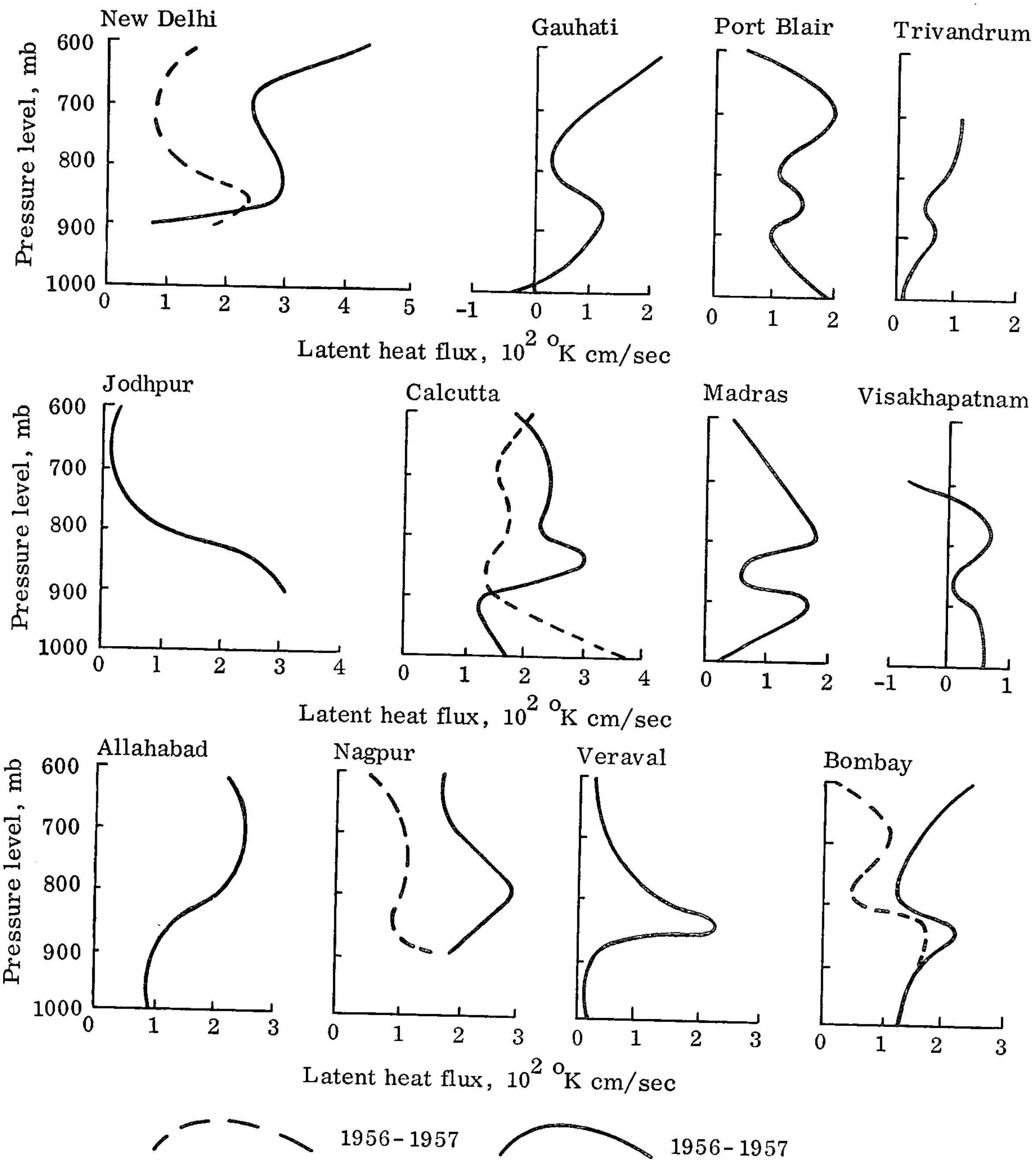

FIG. 3. Vertical variation of latent heat flux.

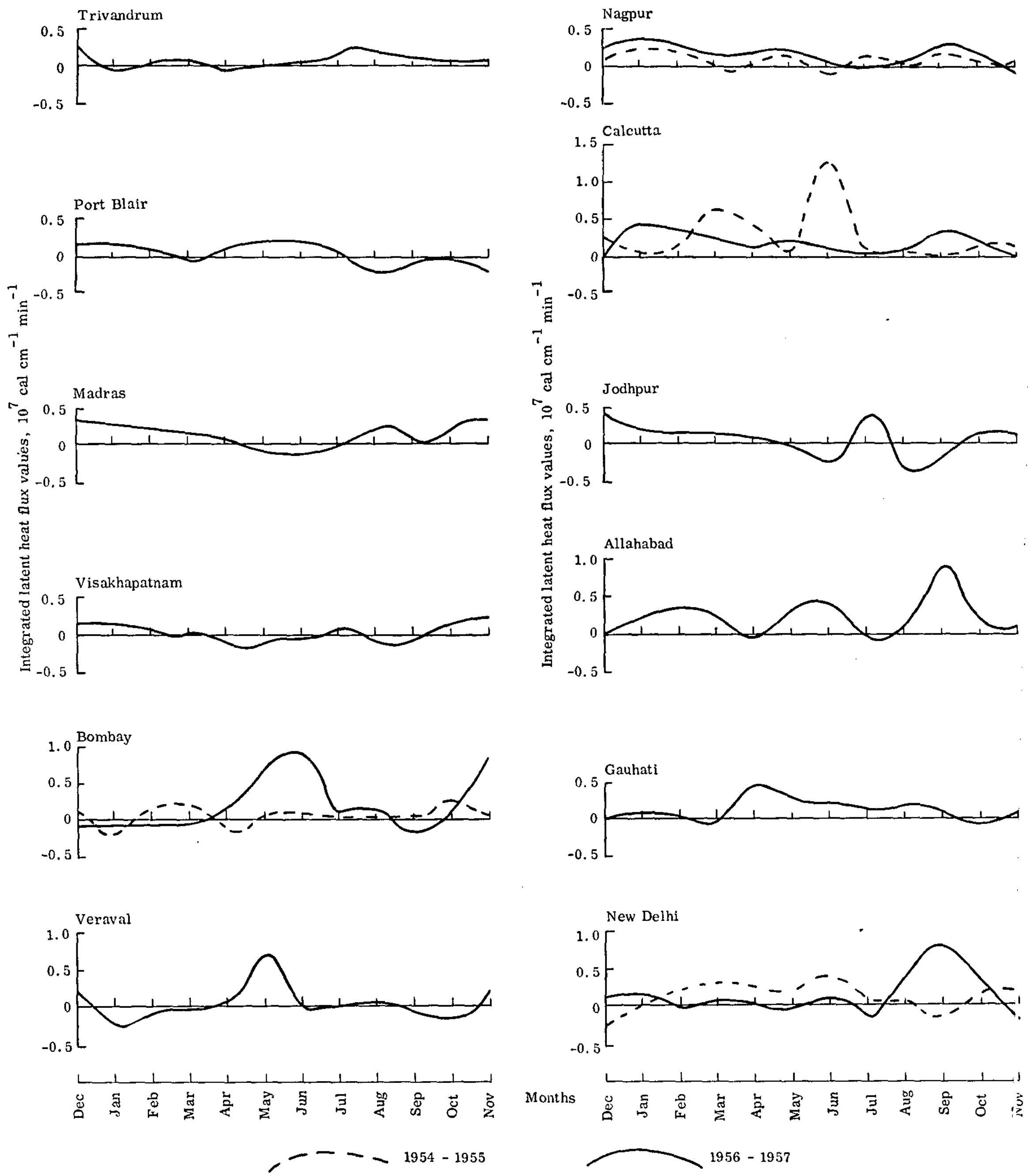

FIG. 4. Monthly variation of integrated latent heat flux.

TABLE 1.

Latitude	29°	26°	21°	18.5°	13°	8.5°
A) Eddy transport of sensible heat (10^7 cal cm^{-1} min^{-1})	−0.15	−0.06	−0.07	−0.09	−0.00	−0.01
B) Eddy transport of latent heat (10^7 cal cm^{-1} min^{-1})	0.17	0.12	0.17	0.11	0.06	0.04
C) Total eddy transport of heat (10^7 cal cm^{-1} min^{-1})	0.02	0.06	0.10	0.02	0.06	0.03
D) Radiation balance requirement after Houghton (10^7 cal cm^{-1} min^{-1})	2.03	1.79	1.46	1.30	0.91	0.61
$\frac{B}{D}$ Latent heat (per cent)	8.4	2.4	11.6	8.5	6.6	6.6
$\frac{C}{D}$ Total heat (per cent)	1.0	3.4	6.9	1.5	6.6	4.9

Fig. 3 depicts the mean annual local eddy flux of latent heat plotted against pressure level for all stations. One can infer from these curves that the local eddy flux of latent heat is comparable in magnitude to that of the local eddy flux of sensible heat and is directed generally northwards at all stations at all levels. This result falls in line with that of the earlier workers (e.g., Peixoto, 1958) who also observe a positive eddy flux of latent heat. Secondly, it can be observed that below 500 mb the eddy flux of latent heat does not show any gradual decrease with altitude, suggesting that levels higher than the 500-mb level have to be taken into account when evaluating this flux in the tropics.

In view of this special vertical variation of sensible and latent local eddy heat fluxes, it is felt that the effect of such data truncation at the 300-mb and 500-mb levels must be studied in the future, with the aid of better data.

Fig. 4 gives the monthly variation of the vertically-integrated latent heat flux at all stations. The curves show a considerable poleward flow in winter months. Another peak in poleward flow occurs at Gauhati, Veeraval, Calcutta, Bombay and Port Blair either in late summer or early monsoon period when the monsoon generally sets in at these stations. The flux is nowhere uniformly strong during the monsoon and post-monsoon months, reflecting the pulsating character of the monsoon.

A look at the broken and full curves in Figs. 1 to 4 suggests that the local eddy flux can exhibit significant differences from year to year.

Now an attempt may be made to compare the total local eddy heat flux with that of the radiation balance requirements reported by Houghton (1954). This comparison is based on the doubtful assumption that the following stations are representative of the entire latitude circles on which they approximately lie:

Delhi	—29N
Gauhati, Allahabad and Jodhpur	—26N
Calcutta, Nagpur and Veeraval	—21N
Bombay and Visakhapatnam	—18.5N
Madras and Port Blair	—13N
Trivandrum	—8.5N

In Table 1 are given the total, sensible and latent, local eddy heat flux values, against the balance requirements, expressed as percentages of the latter. Needless to say, this table clearly shows that the local eddy heat flux measured from 1000-mb to 300-mb levels is too small to account for the necessary transport at these latitudes. In view of the assumptions involved in this study, these results may be treated as provisional until a conclusive study for the tropics is made.

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