On the estimates of heat and moisture over the Indian monsoon trough zone

By T. S. S. ANJANEYULU, *Meteorological office, Poona 5, India*

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ABSTRACT

Based on mean radiosonde/Rawin data for July–August for stations around the monsoon trough over India estimates of sensible and latent heat energy through the entire troposphere have been made. A quasi-eliptical boundary defined by 17 aerological stations containing the monsoon trough has been chosen for the study.

The mean tropospheric circulation is briefly described.

Mass and energy fluxes are evaluated. The computations show mass inflow at all levels up to 600 mb and outflow above 500 mb. The total energy shows a maximum in the lower troposphere and in the upper troposphere with a minimum in the middle troposphere. The flux computations show an export of sensible heat of 8.8×10^{18} calories per day and an import of 16.07×10^{18} calories per day through latent heat.

Introduction

The southwest monsoon over India and the further East is the largest known local perturbation and the most important among the seasonal standing eddies in general circulation. This is much more important in view of very heavy average rainfall during the period the annual variations of which have a great impact on the national economies of the respective countries. The westerly air blowing north of the equator converges into a well known monsoon trough (equatorial trough in summer) over India and the upper flow is carried off by the prevailing easterlies aloft. The upper outflow of sensible heat from the troposphere overlying the trough zone occurs chiefly in the upper limb of the meridional mass circulation of the atmosphere low lattitude cell in the hemisphere.

Riehl & Malkus (1958) examined the heat source in the equatorial trough zone, a belt of 10° latitude to the winter side of the trough around the globe. They examined the broad climatic structure of the trough zone utilising all available climatological data within the belt. However, they suggested that variations in trough structure must be studied in detail as energy properties vary widely with longitude. Berson (1961) examined the energy content of the tropical monsoon trough zone using data from Malaysia, Indonesia and north Australia and has shown that the mean mass circulation associated with the monsoon is a determining factor of the horizontal transport of energy.

The present study concerns itself with the estimation of heat and moisture over the Indian monsoon trough zone. The work essentially consists of volume integration of energy equations and evaluation of energy fluxes by line integrals around the chosen periphery containing the active monsoon trough zone. Although a study of this nature has obvious limitations, it serves, however, a useful purpose in showing the relative magnitudes of different parameters.

Area of study and data used

The selection of the area of study is generally dictated by the location of wind and temperature sounding stations. However, for this study a quasi-elliptical boundary defined by 17 aerological stations (10 RS/Rawin stations and 7 Pilot Balloon stations) henceforth termed "monsoon ellipse" has been chosen for flux calculations. The area is suitable in that besides having a large number of aerological stations around it includes the region of active monsoon trough. Fig. 1 shows the monsoon ellipse with the aerological stations shown around its periphery. Also shown in it are the mean tracks of monsoon depressions which concentrate the rainfall in this season and the normal dates of onset of monsoon.

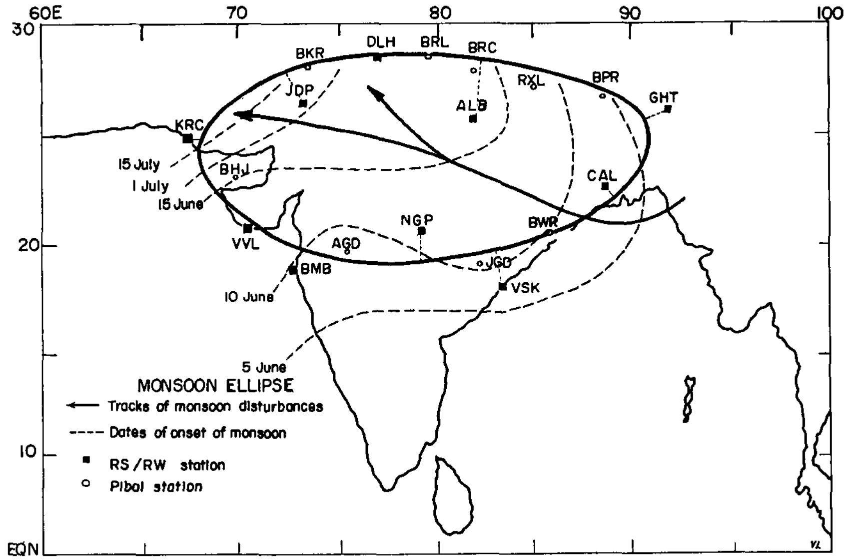


Fig. 1. Monsoon ellipse with aerological stations shown around it. Mean tracks of monsoon disturbances (thick lines) and normal dates of onset of monsoon (broken lines) shown.

The area enclosed in the ellipse is equal to 19.65×10^{15} cm^2. Lateral boundary of the ellipse 6.6×10^8 cm. In the region of assessment of heat and moisture June is mostly a pre-monsoon month for the northern part while the monsoon is established over most of the southern parts and eastern parts of the area. By the first week of July the monsoon regimed is well established over the whole area of the ellipse. However, in September it is irregular and fluctuating in the region. As July–August forms the active monsoon period over this area mean data for this period have been used for his study. Mean radiosonde/rawin data (1956–60) for the stations for July and August have been utilised. Pibals are selective under monsoon conditions. However, they have been utilised as they are based on generally long periods and serve only as gaps between larger net work of radiosonde/Rawin stations on the boundary of the ellipse in the absence of any other solution to utilise all available data.

Mean tropospherical circulation over India and neighbourhood

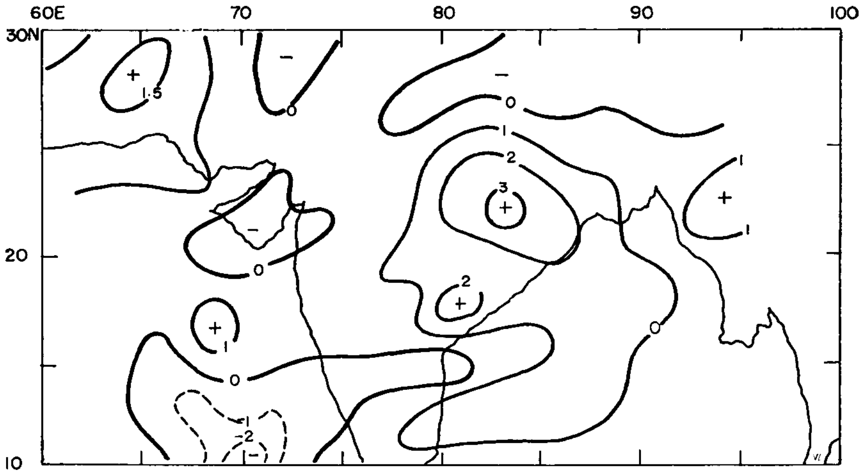
The mean tropospherical climatological circulation over India during the monsoon season is too well known. However, the same is depicted in a nutshell through relative vorticity and relative divergence charts and mean zonal and meridional cross sections along longitude 77° E.

The relative vorticity fields at 850 mb and 200 mb are shown in Figs. 2*a* and *b* respectively. A region of cyclonic vorticity of 3×10^{-5} sec^{-1} lies to the southeast of the monsoon ellipse as distinct from a comparatively lower cyclonic vorticity of 1.5×10^{-5} sec^{-1} over West Pakistan where an active surface low lies during the period. At 200 mb a region of anticyclonic vorticity of 1.5 to 2.5×10^{-5} sec^{-1} lies over the eastern parts of the monsoon ellipse.

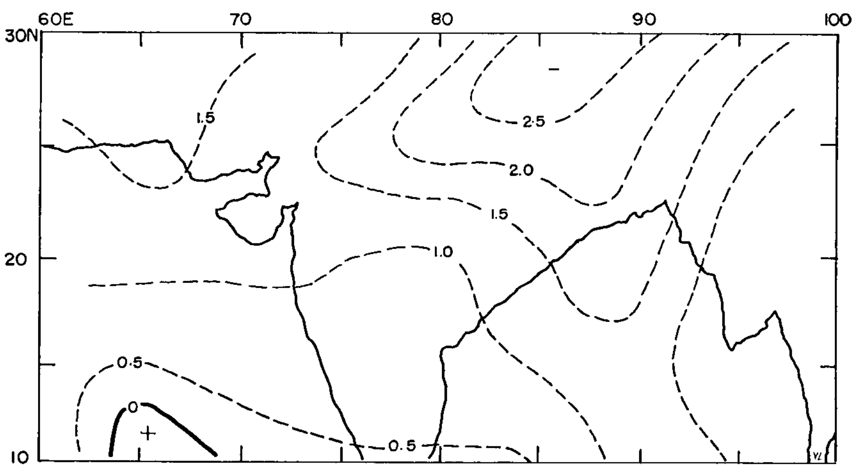
The field of relative vergence at 850 and 200 mb are shown in Figs. 3*a* and *b* respectively. A region of convergence of 2×10^{-5} sec^{-1} lies over the eastern side of the ellipse at 850 mb while there is divergence to its west. At 200 mb the region of divergence lies over the eastern parts of the ellipse whereas there is convergence to the west.

Fig. 4*a* shows the vertical cross section of the mean zonal component of wind along longitude 77° E. The westerly monsoon current is strongest with mean speed of 20/25 knots over the south peninsula at 800 mb. The upper easterly current is 70 knots strong between 150 and 100 mb over the southern latitudes. The dotted lines in the figure show the anomalies of temperature from the mean.

Palmen *et al.* (1958) showed that for main-



a



b

Fig. 2. (*a*) 850 mb relative vorticity fields. Unit: 10^{-5} sec^{-1}, Cyclonic (positive). (*b*) 200 mb relative vorticity field. Unit: 10^{-5} sec^{-1}, cyclonic (positive).

tenance of tropical meridional cell equatorward motion takes place at low levels and ascent to high troposphere along the equatorial trough and a return flow poleward aloft with a descent in subtropics. But this outflow from equatorial trough does not occur uniformly around the globe but takes place in a few narrow channels (Riehl & Malkus, 1958). Shown in Fig. 4*b* is the vertical cross section of mean meridional components of wind along longitude 77° E. Meridional components are poleward in the lower troposphere across the trough. North of the trough they are poleward in the upper toposphere. The monsoon southerlies extend up to 600 mb at latitude 20° N while their depth is limited to 900 mb at latitude 30° N. During this period the northward extent of the tropical meridional cell is largest over Indian longitudes as different from other longitudes, say longitude 40° E (Rao, 1962), and pictures out the longitude variable circulation of the troposphere in this region of the globe.

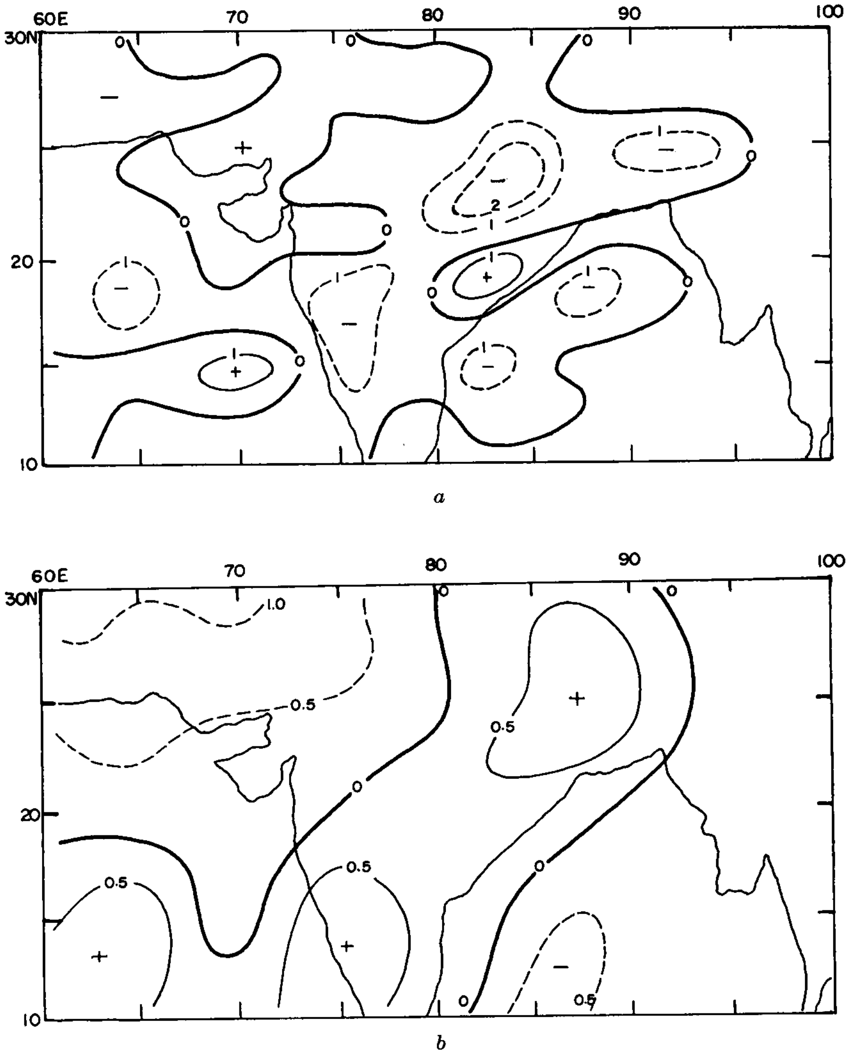


Fig. 3. (*a*) Mean (July–August) 850 mb vergence field. Unit: 10^{-5} sec^{-1} (divergence, positive). (*b*) Mean (July–August) 200 mb vergence field. Unit: 10^{-5} sec^{-1} (divergence, positive).

Atmospheric heat and energy balance equations

Notation

A	Reciprocal of the mechanical equivalent of heat
Cp	Specific heat of air at constant pressure
Cn	Component of wind normal to the ellipse
Cs	Component of wind parallel to the ellipse
F	Frictional force
g	Acceleration due to gravity
L	Latent heat
M	Mass flux
P	Pressure
Q	Specific humidity
S	Perimeter of the monso on ellipse
$\mathbf{V}$	Velocity vector
Z	Contour heights
ϱ	Density

$CpT + Agz$: enthalpy plus potential energy termed in this paper as "sensible heat" or "potential heat".

In the vector form the equation of motion can be written as

$$\varrho \frac{d\mathbf{V}}{dt} = -\nabla P - 2\varrho\Omega \times \mathbf{V} + \varrho g + \varrho F \tag{1}$$

multiplying equation (1) with $\mathbf{V}$ and rearranging the terms it becomes

$$\varrho \frac{d}{dt}\left(\frac{V^2}{2} + AgZ\right) = -\mathbf{V}\cdot\nabla P + \varrho \mathbf{V}\cdot\mathbf{F}, \tag{2}$$

this being an expression for the total change of kinetic energy and potential energy in terms of rate of work done by pressure forces and through frictional dissipation. If Q is the heat added or withdrawn from the system, then the first law of thermodynamics can be written as

$$\frac{dQ}{dt} = Cp\frac{dT}{dt} - \frac{1}{\varrho}\frac{dP}{dt} \tag{3}$$

subtracting equation (2) from equation (3) and substituting

$$\frac{\partial P}{\partial t} + \mathbf{V}\cdot\nabla P \quad \text{for} \quad \frac{dP}{dt}$$

equation (3) becomes

$$\varrho\frac{dQ}{dt} = \varrho\frac{d}{dt}\left(Cp\,T + AgZ + \frac{V^2}{2}\right) - \frac{\partial P}{\partial t} - e\mathbf{V}\cdot\mathbf{F}, \tag{4}$$

this being the expression for changes in energy in all forms. Utilising the equation of continuity, equation (4) becomes

$$e\frac{dQ}{dt} = \frac{d}{dt}\varrho\left(Cp\,T + AgZ + \frac{V^2}{2}\right) + \nabla\cdot\varrho\mathbf{V}\left(Cp\,T + AgZ + \frac{V^2}{2}\right) - \frac{dP}{dt} - \varrho\mathbf{V}\cdot\mathbf{F}. \tag{5}$$

As the computations are made over a long period, neglecting local changes, equation (5) becomes

$$\varrho\frac{dQ}{dt} = \nabla\cdot\varrho\mathbf{V}\left(Cp\,T + AgZ + \frac{V^2}{2}\right) - \varrho\mathbf{V}\cdot\mathbf{F}. \tag{6}$$

The energy equations can be integrated for a large non-homogeneous system where boundary surface has any shape by transferring the equation to a unit volume and integrating over the whole volume of the system.

On integrating equation (6) over an element of atmospheric volume $d\alpha$ and applying divergence theorem equation (6) becomes

$$\int \varrho\frac{dQ}{dt}d\alpha = \iint Cn\left(Cp\,T + AgZ + \frac{V^2}{2}\right)\frac{e\,ds\,dZ}{g} - \int \varrho\mathbf{V}\cdot\mathbf{F}\,d\alpha, \tag{7}$$

where Cn is the component of wind normal to the boundary (positive outward) and ds the peripheral distance around the boundary. The integral on the left hand side of the equation represents the heat sources and sinks. The terms to the right represent the total energy flux and frictional dissipation of kinetic energy within the volume. Equation (7) after changing the vertical co-ordinate in the flux integral becomes

$$Qs + Qp - R = \iint Cn\,(Cp\,T + AgZ)\frac{ds\,dp}{g} + \int \varrho\mathbf{V}\cdot\mathbf{F}\,d\alpha, \tag{8}$$

where R is the net radiational cooling, Qp the precipitation heating and Qs the surface sensible heat source, this equation representing the requirement of sensible heat balance. Similarly the latent heat balance equation can be written as

$$Qp - Qe = \iint Cn\,Lq\frac{ds\,dp}{g}, \tag{9}$$

where Qe is the surface latent heat source.

Evaluation of heat content of monsoon ellipse troposphere

For each station on the boundary of the monsoon ellipse data for each element (wind, temperature, dewpoint and contour value), for each level from surface to 100 mb at intervals of 100 mb and for 150 mb have been collected. Then using the number of observations in each month the integrated July–August means for different element were obtained. As the number of observations decreased with height vertical profiles for each station and elements were plotted against pressure to check their internal consistency. Then the mean value of different

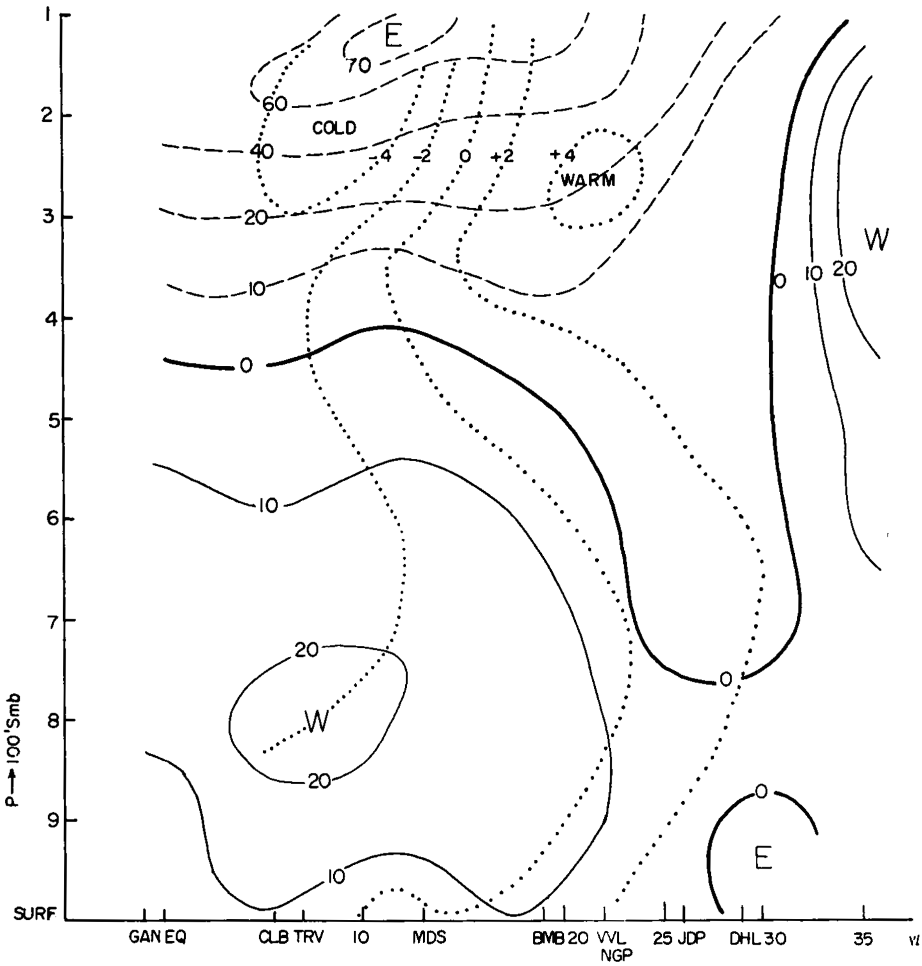


Fig. 4 *a*

Fig. 4. (*a*) Vertical cross-section of the mean (July–August) zonal component of wind along longitude 77° E. Westerlies (continuous lines); easterlies (dotted line). Unit: knots. (*b*) Vertical cross section of the mean (July–August) meridional component of wind along longitude 77° E (*P*, poleward; *E*, equatorward) knots.

elements for each layer was picked out for each station.

Then vertical space sections were prepared for each of the elements with pressure on the linear scale as ordinate and the peripheral distance as abscissae. After the analysis of the space sections fifteen equally spaced points around the monsoon ellipse were chosen. Values of each element for each layer of 100 mb thickness were read out from the analysis at each of the 15 grid points. This procedure was adopted in order to weight all the stations around the boundary irrespective of the spacings of these stations. These 15 values were averaged horizontally to yield the mean value around the ellipse for each layer. Table 1 shows the enthalpy plus potential energy $CpT+gZ$, latent heat energy (Lq) and total energy ($CpT+Lg+AgZ$) averaged around the periphery of the ellipse by the procedure detailed above.

An examination of the values in Table 1 shows that the energy content for the monsoon ellipse troposphere exceeds that of the broad trough zone (Riehl & Malkus, 1958).

As moisture gradients in tropics are small, being particularly so in the equatorial trough zone, the deviations of latent heat (Lq) in

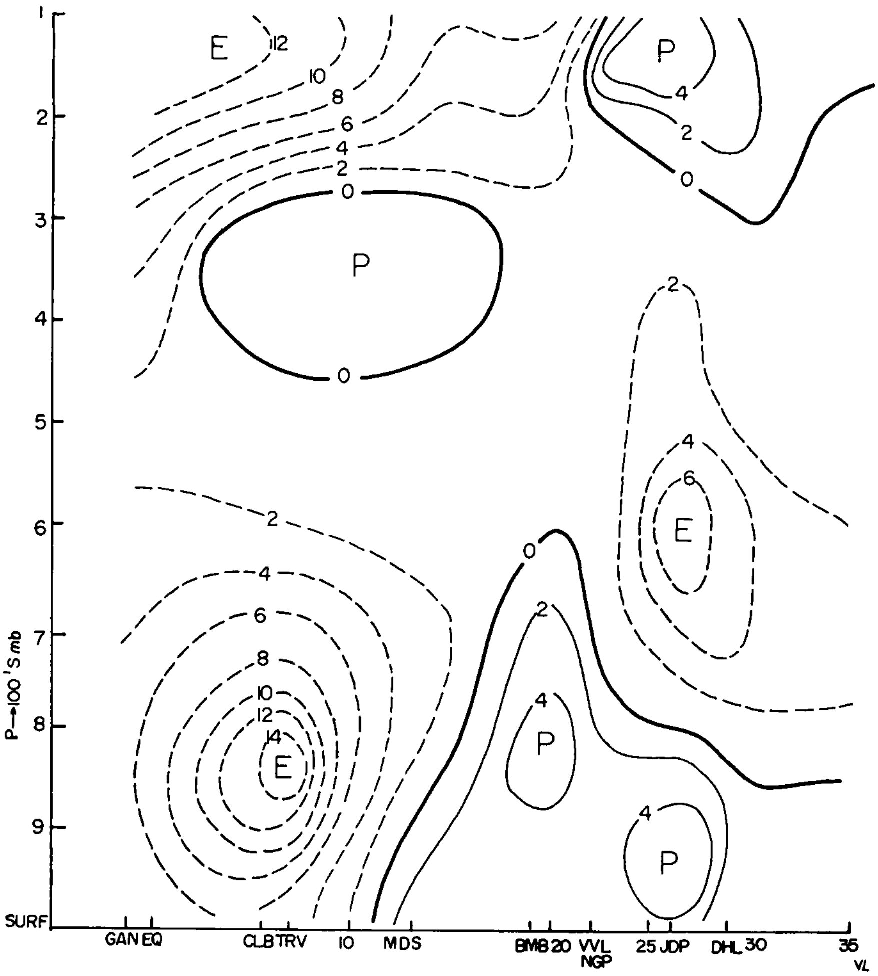


Fig. 4 b

tenths of cal gm^{-1} at individual stations from the mean around the boundary are worked out and the vertical profile is shown in Fig. 5. High positive values are noticed between 800 and 700 mb on the eastern half of the elliptical boundary. Large negative values are noticed towards the western end of the boundary indicating relatively marked dryness of the air. However, around Nagpur and Visakhapatnam the deviations are negative up to lower middle troposphere. It is interesting to note that monsoon westerlies over Nagpur and Visakhapatnam show relative dryness in comparison to Bombay and Calcutta.

The vertical profiles of the mean distribution of sensible heat and total energy are shown in Fig. 6. While the sensible heat energy increases with height the latent heat energy decreases with height, as a consequence the total energy shows a maximum in the lower and the upper troposphere with a minimum in between. This occurs in the layer 600–500 mb. The values of Lq above 400 mb have been neglected.

Heat and moisture fluxes

The flux integrals of sensible heat and latent heat shown in equations 8 and 9 can be broken up into contributions of mean and eddy motions. The contributions of eddy motions arise from two factors: one being due to variation of wind and other parameters around the boundary

Table 1. *Mean energy of the monsoon ellipse troposphere*

Unit: cal gm^{-1}

Pressure 100's mb	Enthalpy CpT	Potential energy (Agz)	Latent heat Lq	Potential heat or sensible heat $CpT + Agz$	Total energy $Cpt + Agz + Lq$
Surface 9	72.0	1.5	10.8	73.5	84.3
9–8	70.5	3.5	8.8	74.0	82.8
8–7	69.1	6.1	6.3	75.2	81.5
7–6	67.4	8.7	5.3	76.1	81.4
6–5	65.9	11.9	3.3	77.8	81.1
5–4	63.6	15.7	1.8	79.3	81.1
4–3	60.8	20.4	—	81.2	81.2
3–2	57.1	26.0	—	83.1	83.1
2–1.5	53.1	31.5	—	84.6	84.6
1.5–1	50.1	36.0	—	86.1	86.1

(space eddy terms) and the other due to variations in time. As the study is based on bimonthly mean data the time eddy terms of shorter durations are omitted and hence the eddy motions referred to here are space eddy terms only. The kinetic term energy turns out to be of much smaller order than that of the sensible heat and energy in the latent heat form and hence it is neglected. The sensible heat and latent heat flux terms in equations 8 and 9 when broken up into mean and eddy terms and omitting kinetic energy term become

$$H = \bar{H} + H' = \iint (CpT + AgZ)\, Cn\, \frac{ds\,dp}{g}$$
$$= \iint \frac{\overline{CpT + AgZ\, Cn}\,ds\,dp}{g}$$
$$+ \iint \frac{\overline{(CpT + AgZ)'\,Cn'}\,ds\,dp}{g}, \quad (10)$$

$$L = \bar{L} + L' = \iint Lq\, \frac{Cn\,ds\,dp}{g}$$
$$= \iint \overline{Lq}\, \frac{\overline{Cn}\,ds\,dp}{g} + \iint \frac{\overline{Lq'\,Cn'}\,ds\,dp}{g}, \quad (11)$$

where bars and primes represent mean and eddy motions respectively.

Lateral mass flux

Shown in Fig. 7 is the vertical profile of the normal component of motion at different stations around the lateral boundary of the ellipse. The inflow is maximum near 900 mb at stations to the southeast o
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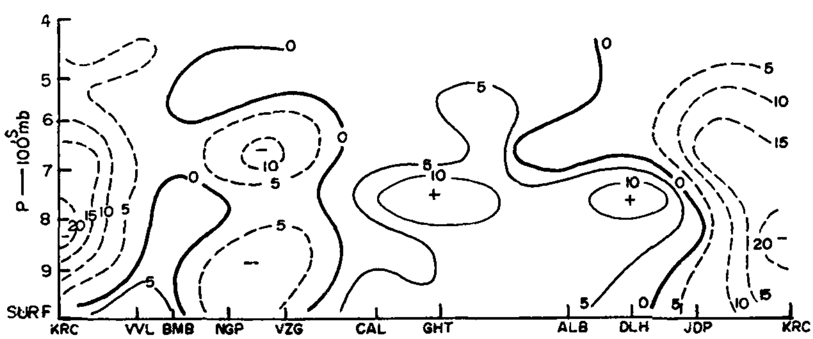


Fig. 5. Vertical profile of the deviations of Lq (in tenths of cal gm^{-1}) from the mean around the boundary continuous line (positive); broken lines (negative).

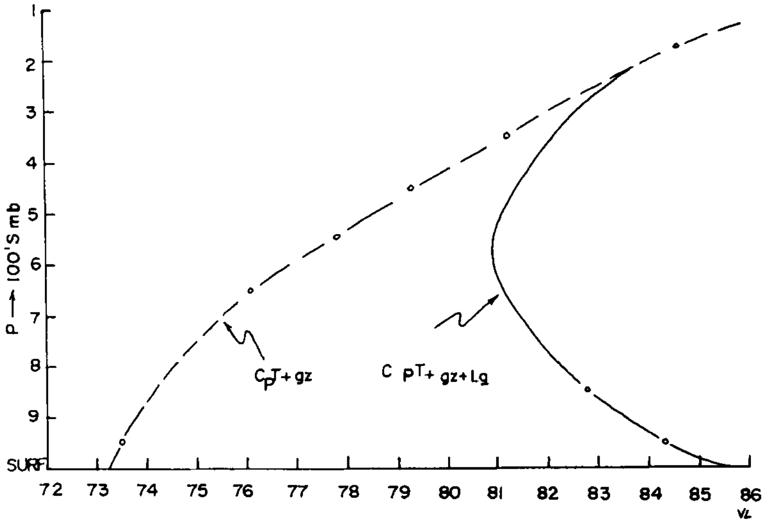


Fig. 6. Vertical profile of the sensible heat ($CpT+gZ$) and total heat ($CpT+gZ+Lq$) averaged around the lateral boundary. Unit: cal gm^{-1}.

sphere near 800 mb to the south and southwest aloft between 150 and 100 mb.

Table 2 shows the values of Cn and the lateral mass flux (positive outward) obtained from the value

$$Cn \frac{ds\,dp}{g}.$$

The vertical profiles of mean components of wind tangential (Cs) to the ellipse and normal (Cn) to the ellipse obtained by averaging the values around the boundary are shown in Figs. 8*a* and *b* respectively. The tangential circulation is cyclonic up to about 400 mb and anticyclonic above it. Maximum cyclonic components are obtained near 900 mb. The normal components are inward up to 600 mb and outward above 500 mb. This only goes to show the decrease in intensity of the monsoon trough convergence with height and its reversal aloft. The outflow is largest above 300 mb and occurs in the divergent easterly flow at the southern periphery of the upper tropospheric quasistatic ridge over south Asia over the region of low level trough.

Table 2. *Normal component of motion averaged around the boundary (Cn) and the lateral mass flux (positive outward)*

PPP (100's mb)	*Cn* (knots)	Lateral mass flux unit 100^{15} gm day^{-1}
Surface 9	−2.1	−0.63
9–8	−1.9	−0.57
8–7	−1.6	−0.48
7–6	−0.4	−0.12
6–5	0	0
5–4	0.3	0.09
4–3	1.2	0.35
3–2	2.2	0.66
2–1.5	2.2	0.34
1.5–1	2.4	0.36
Surface −5	−6.0	−1.8
5–1	6.0	1.8
Surface 1	0	0

The sensible heat and latent heat fluxes around the boundary have been evaluated employing terms in equations 10 and 11 are given in Table 3. A large import of sensible heat energy takes place in the lower troposphere (138.10×10^{18} cal day^{-1}) and a larger export aloft (146.91×10^{18} cal day^{-1}) leaving a net export of 8.81×10^{18} cal day^{-1}.

The moisture flux is negative (inward) at all levels both by mean and eddy motions except for a small export of 0.11×10^{18} cal day^{-1} between 500 and 400 mb levels. Thus a net import of 16.07×10^{18} cal day^{-1} takes place into the ellipse through latent heat.

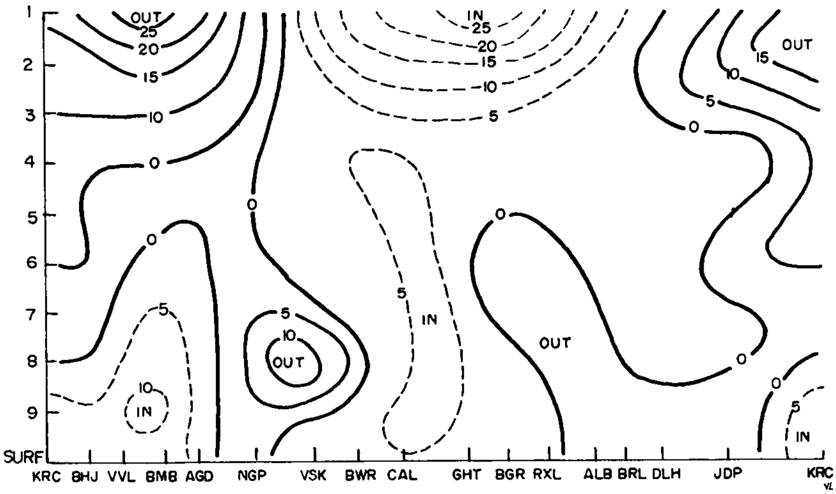
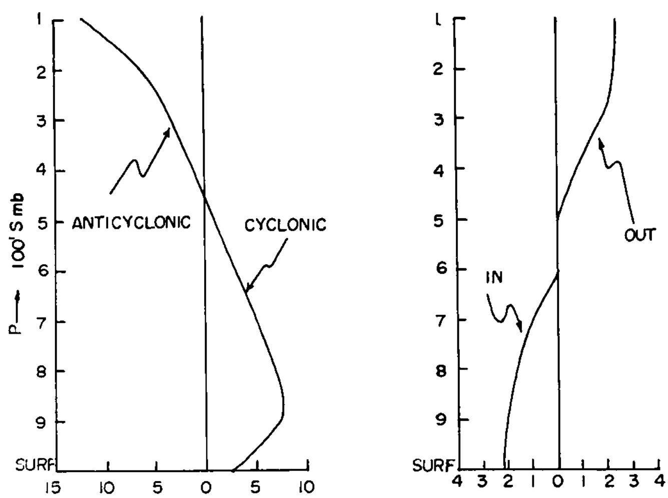


Fig. 7. Vertical profile of the component of wind normal to the boundary at different stations (knots).

Summary and Discussion

Methods used in the study are similar to these employed by Palmen (1958), Riehl & Malkus (1958) and Colón (1960). In this bimonthly (July–August) mean wind and temperature data were used.

The normal components are inward up to 600 mb and outward above 500 mb. In the layer 600–500 mb there is no ageostrophic mass circulation. The total energy shows a maximum in the upper troposphere and lower troposphere with a minimum in the middle troposphere. The computation of fluxes of sensible heat and latent heat shows an import of 16.07×10^{18} cal day^{-1} through latent heat and an export of 8.81×10^{18} cal day^{-1} through sensible heat. An examination of values of energy parameters together with the normal component of wind at individual stations suggests that a larger import of latent heat occurs at the southwestern



a *b*

Fig. 8. (*a*) Vertical profile of the tangential component (Cs) of wind (knots) averaged around the boundary. (*b*) Vertical profile of the normal component (Cn) of the wind (knots) average around the boundary.

Table 3. *Lateral fluxes of CpT + AgZ, Lq and CpT + AgZ + Lq by mean and eddy motions*

Unit: cal day^{-1}

Pressure in 100's mb	Flux of $CpT + Agz$ (Unit: 10^{18} cal day^{-1}) Mean motion	Eddy motion	Net	Flux of Lq (Unit: 10^{18} cal day^{-1}) Mean motion	Eddy motion	Net	Flux of $Cpt + Agz + Lq$ (Unit: 10^{18} cal day^{-1}) Mean motion	Eddy motion	Net
Surface	−46.31	−0.57	−46.88	−6.88	−0.22	−7.02	−53.11	−0.79	−53.90
9–8	−44.00	−0.82	−44.82	−5.02	−0.09	−5.11	−49.02	−0.91	−49.93
8–7	−36.11	−0.80	−36.92	−3.02	−0.04	−3.06	−39.13	−0.84	−39.97
7–6	−9.14	−0.14	−9.28	−0.62	−0.19	−0.81	−9.76	−0.33	−10.09
6–5	0	−0.21	−0.21	0	−0.18	−0.18	0	−0.39	−0.39
5–4	+7.14	−0.33	+6.81	+0.16	−0.05	+0.11	−7.30	−0.38	+6.92
4–3	+24.36	+0.12	+24.48	—	—	—	+24.36	+0.12	+24.48
3–2	+54.84	−0.22	+54.62	—	—	—	+54.84	−0.22	+54.62
2–1.5	+29.20	−0.34	+28.86	—	—	—	+29.20	−0.34	+28.86
1.5–1.0	+33.17	−1.03	+32.14	—	—	—	+33.17	−1.03	+32.14
Surface to 5	−135.56	−2.54	−138.10	−15.46	−0.72	−16.18	−151.02	−3.26	−154.28
5–1	+148.71	−1.80	+146.91	+0.16	−0.05	−0.11	+148.87	−1.85	+147.02
Surface to 1	+13.15	−4.34	+8.81	−15.30	−0.77	−16.07	−2.15	−5.11	−7.26

and eastern portions of the elliptical boundary while their import through the southern stations is relatively smaller. It is interesting to see that in monsoon westerly current Nagpur and Visakapattanam show relative dryness in comparison to Bombay and Calcutta.

The fields of vorticity and divergence at 850 and 200 mb presented in this paper bring out the dissimilarity even within the Indian monsoon trough zone. Active zone of cyclonic vorticity and convergence in the lower troposphere with anticyclonic vorticity and divergence aloft over the eastern portions of the ellipse with almost opposite features over the western portion. The flow pattern being favourable for active development of weather in the eastern portion and otherwise in the western portion of the ellipse. Vertical velocity patterns (Das, 1962) over the region of the ellipse are also in general agreement with the above features. Studies of Ramasastry (1955) have shown poleward time eddy fluxes of heat and moisture at stations over the eastern part while being equatorward over the western parts. This inhomogeneity of the area is a limitation in this study. Hence a detailed examination of sensible and latent heat fluxes over the eastern parts and western parts of the monsoon ellipse is likely to throw more light into the energetics of the trough zone.

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ОБ ОЦЕНКАХ ТЕПЛА И ВЛАЖНОСТИ В ИНДИЙСКОМ МУССОНЕ

Проделаны оценки обычной и скрытой тепловой энергии в тропосфере, основанные на средних радиозондовых данных за июль–август для станций на территории Индии в период муссона. Для изучения была выбрана квази-эллиптическая граница, определенная 17-ю аэрологическими станциями, через которые проходил муссон. Коротко описывается средняя тропосферная циркуляция. Оцениваются потоки массы и энергии. Вычисления показывают втекание массы на всех уровнях вплоть до 600 мб и вытекание выше 500 мб. Полная энергия обнаруживает максимумы в нижней и верхней тропосфере и минимум в средней тропосфере. Вычисления потоков показывают отток обычного тепла порядка $8{,}8 \times 10^{18}$ калорий в день и приток скрытого тепла порядка $16{,}07 \times 10^{18}$ калорий в день.