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Vertical motion in the Indian summer monsoon

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ABSTRACT. The vertical motion field in the Indian monsoon region has been studied for mean July, a strong monsoon day (7 July 1963) and a weak monsoon day (19 July 1963). We have used the quasi-geostrophic ω equation for this purpose. In addition to forcings due to thermal and differential voriticty advection, the vertical motion due to orography and friction have been included. The vertical motion due to the different forcing functions have been computed. The cumulative ω -field due to all forcing functions and due to individual forcing functions together with their vertical profiles are delineated.

Conversion from potential to kinetic energy associated with the vertical circulations have been computed and presented in this paper. It is seen that the meridional circulation in the y-p plane is very marked on 7 July with ascent over north India and descent to the south. On 19th, however, uniform descent is seen everywhere. There is conversion from zonal available potential energy to zonal kinetic energy on the day of active monsoon. The conversion is much smaller on the day of weak monsoon. Other energy conversions are also discussed.

1. Introduction

Estimates of conversion from potential into kinetic energy involve the vertical p velocity. Vertical motion and associated circulations during the monsoon have been discussed by Das (1962), Saha (1968), Koteswaram (1960), Rao (1962), Asnani* and Keshavamurty (1971). Vertical motion associated with monsoon depressions have been studied by Rao and Rajamani (1970). In this paper we have computed vertical motion in the Indian monsoon region for mean field in July and for two contrasting monsoon situations, using the quasi-geostrophic ω equation with friction and orography.

2. Data and computations

Quasi-geostrophic ω and energy conversions have been computed for the mean field in July, on a strong monsoon day, *i.e.*, 7 July 1963 and on a weak monsoon day, *i.e.*, 19 July 1963. These situations were earlier studied by Raman *et al.* (1965). Fig. 1 shows the 1000 mb charts for these two dates. It is seen that the monsoon trough has shifted to the foot of the Himalayas on the weak monsoon day.

We have used height data for 1000, 850, 700, 500 300, 200 and 100 mb and have computed ω at 850, 700, 500 and 300 and 200 mb. The area for which computations are made is from 5° to 22.5° N and 55° to 95°E.

3. Quasi-geostrophic ω equation

The vorticity equation is given by

$$\frac{\partial \xi}{\partial t} + \mathbf{V}.\nabla\ (\xi + f) = f_0\ \frac{\partial \omega}{\partial p} \qquad (1)$$

*Personal communication

Thermodynamic energy equation for adiabatic motion is given by

$$\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial p}\right) + \mathbf{V}.\nabla\left(\frac{\partial \phi}{\partial p}\right) + \sigma\,\omega = 0 \qquad (2)$$

$$\xi = \frac{1}{f_0}\nabla^2 \phi = \nabla^2 \psi \qquad (3)$$

$$\sigma = -\frac{\alpha}{\theta}\ \frac{\partial \theta}{\partial p} \qquad (4)$$

$$\mathbf{V} = \mathbf{k} \times \frac{g}{f}\ \nabla z \qquad (5)$$

Static stablity parameter is taken as constant in any isobaric surface, *i.e.*, $\sigma = \sigma\ (p)$

Using Eqns. (1) and (2) we obtain the quasi-geostrophic ω equation.

$$\sigma\,\nabla^2 \omega + f_0^2\ \frac{\partial^2 \omega}{\partial p^2} = g\ \frac{\partial}{\partial p}\ J\,(z,\eta) - \frac{g^2}{f_0}\nabla^2 J\left(z, \frac{\partial z}{\partial p}\right) \qquad (6)$$

$$\eta = \frac{g}{f_0}\ \nabla^2 z + f \qquad (7)$$

Eq. (7) is the quasi-geostrophic omega equation. The first term on the right hand side of Eq. (6) is the forcing due to vorticity advection while the second term is the forcing due to thermal advection. These forcing functions can be calculated from a specified height field.

We have solved this equation by three dimesional relaxation with 2.5° mesh grid. At the side walls and at the top of the domain, the boundary condition was ω=0. At the bottom, we

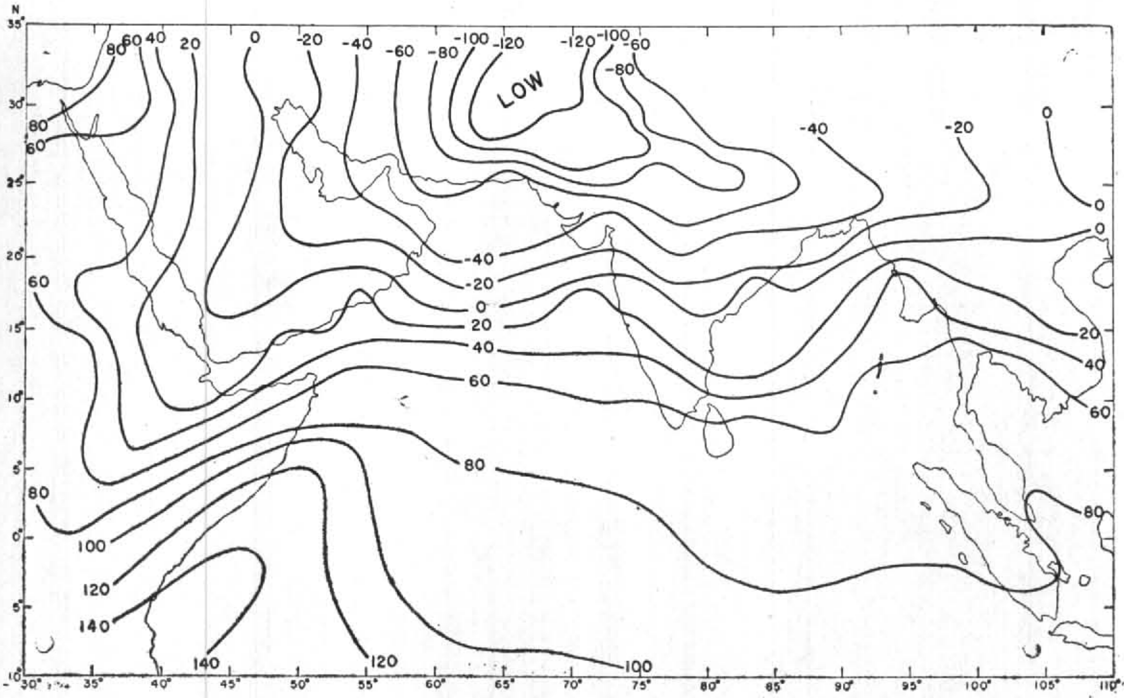


Fig. 1(a)

1000 mb height field (gpm) on 7 July 1963

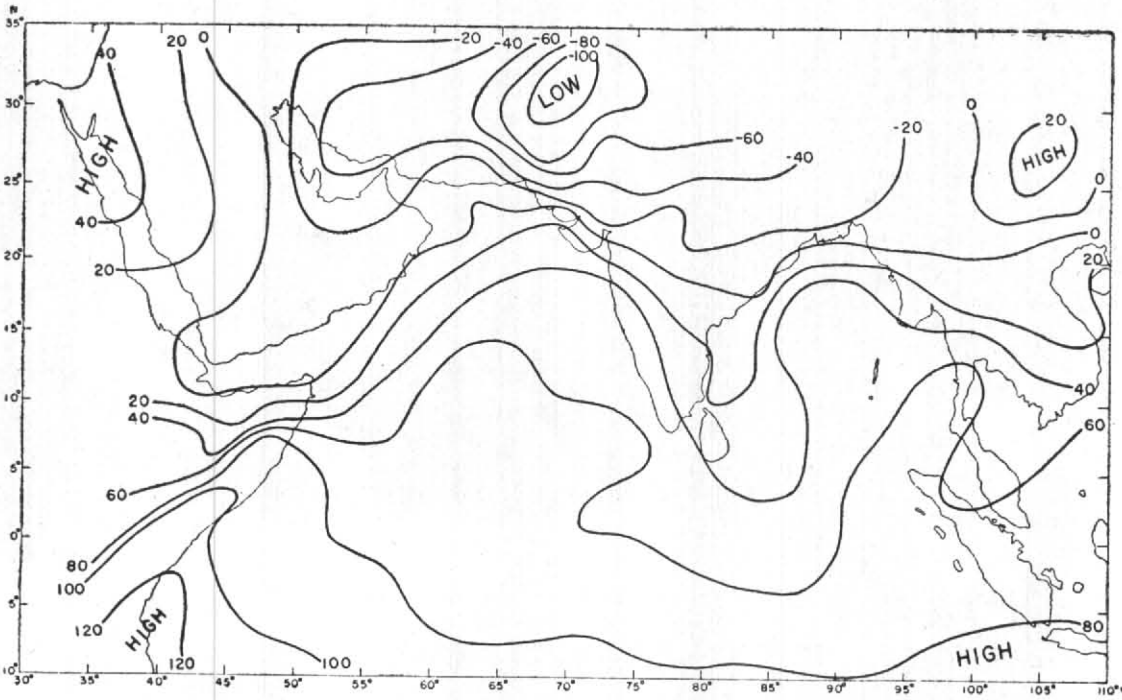
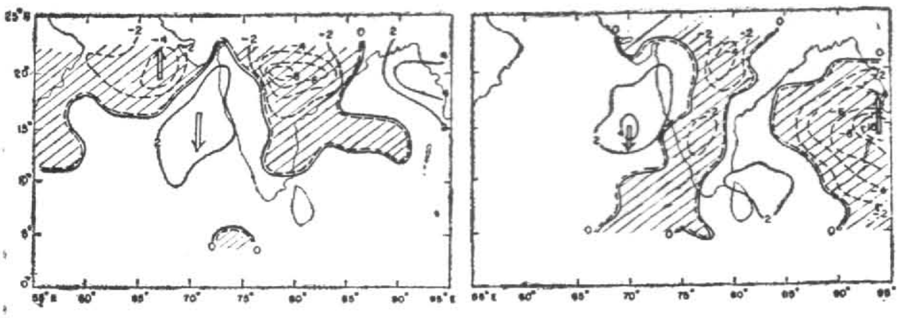


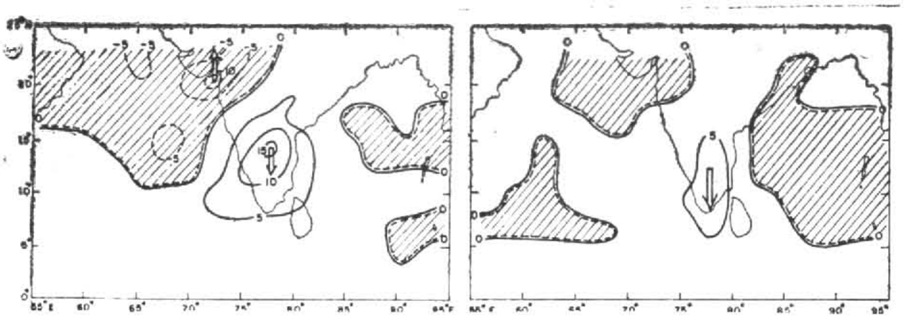
Fig. 1(b)

1000 mb height field (gpm) on 19 July 1963



(a). 700mb (b). 300 mb

Fig. 2. ω due to all (10^{-4} mb/sec) mean July



(a). 700 mb (b). 300 mb

Fig. 3. ω due to all (10^{-4} mb/sec), 7 July 1963

used the contribution to ω due to friction and orography.

We have used Charney and Eliassen's (1949) formulation for the frictional ω. Using Ekman theory of airflow in the frictional layer, the frictional ω at the top of frictional layer is

$$\omega_F = - g\rho \frac{\sqrt{k}}{2f_0} \sin 2\alpha \, (\xi_g)_0$$

where,

k = coefficient of eddy viscosity (10 m^2/sec)

α = the angle of inflow ($22\frac{1}{2}°$)

ρ = air density in the Ekman layer ($1 \cdot 00 \times 10^3$ gm. m^{-3})

$(\xi_g)_0$ = geostrophic vorticity at 1000 mb

$f_0 = f_{15°}$ = coriolis parameter at latitude 15°N (3.775×10^{-5} sec^{-1})

The orographic ω was obtained by

$$\omega = - g\rho \, (\mathbf{V}_{g1000}, \nabla h)$$

where h is the height of terrain above, sea level, taken from Berkofsky and Bertoni (1960). As the above ω equation is linear, we partition the ω due to different forcing effects and also ω due to the lower boundary conditions.

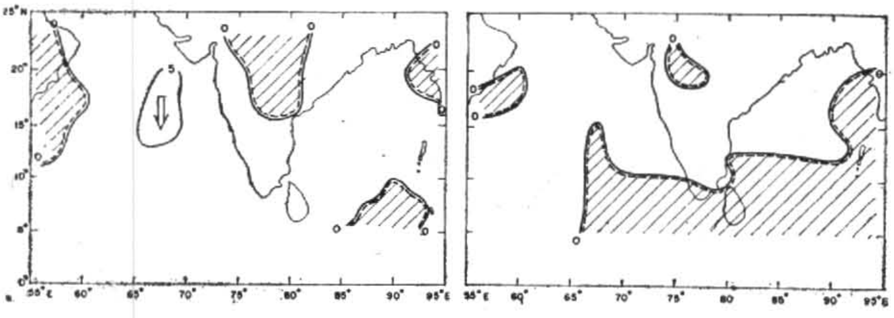
We shall include the effect of latent heat in later studies.

As we have used the quasi-geostrophic system, we shall view the results for low latitudes with some reservation.

4. Results and discussion

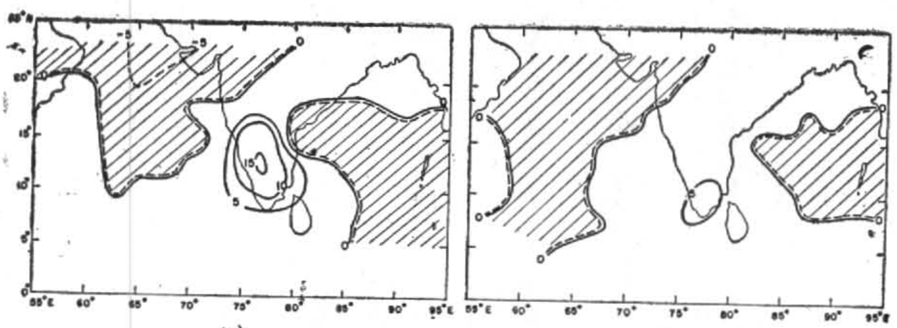
Fig. 2 shows the field of ω for mean July at 700 and 300 mb. At 700 mb there are two centres of upward motion, one over east Madhya Pradesh and Orissa and another off Saurashtra, Konkan coasts. These regions of upward motion extend from 850 to 300 mb over east M. P. and from 850 to 500 mb and over northeast Arabian Sea respectively. A region of descent was found over central Arabian Sea at 850 mb. There is a region of descent over east Arabian Sea from 700 to 200 mb. At 500, 300 and 200 mb an east-west circulation with ascent over Andaman Sea and descent over east Arabian Sea is seen. The field of ω over India and neighbourhood was obtained by Das (1962). He found a region of strong ascent over northeast India and one of strong descent over northwest India-Pakistan. Our area of computation does not cover these regions.

Fig. 3 shows similar ω-charts for 7 July 1963, which was an active monsoon day (for the same levels). At 850 mb we have a region of strong ascent over west Madhya Pradesh and neighbourhood. This was in association with a depression. There is ascent over north Arabian Sea also in connection with the mid-tropospheric system. These regions of ascent are seen at 700 mb also,



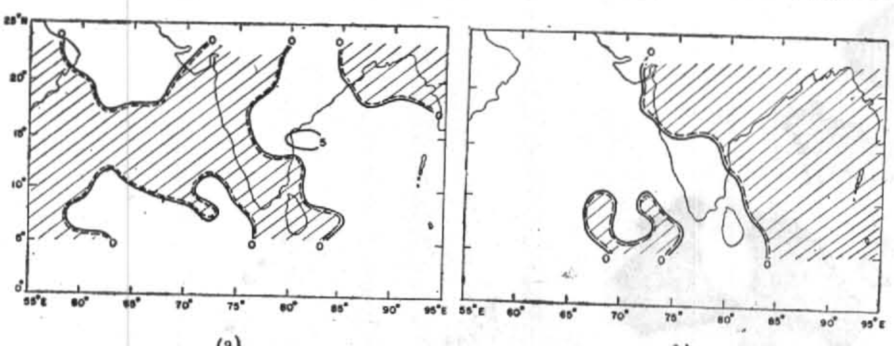
(a). 700 mb (b). 300 mb

Fig. 4. ω due to all (10^{-4} mb/sec), 19 July 1963



(a) (b)

Fig. 5. ω due to thermal advection (10^{-4} mb/sec) on 7 July 1963 at (a) 700 mb and (b) 300 mb



(a) (b)

Fig. 6. ω due to vorticity advection (10^{-4} mb/sec) on 7 July 1963 at (a) 700 mb and (b) 300 mb

There is a region of strong descent in south Peninsula from 850 to 300 mb. As the data coverage on these dates was very good, the differences on the different dates are believed to be genuine.

Fig. 4 shows similar charts for 19 July 1963, a weak monsoon day, when the monsoon trough had shifted to the foot of the Himalayas. Except for a region of ascent over Gujarat at 850 mb generally descending motion is noticed throughout.

Let us now look at the partitioned ω due to the various forcings on 7 July 1963. Figs. 5 and 6 show the partitioned ω for 700 and 300 mb, due to thermal advection and vorticity advection respectively for 7 July 1963. It is seen that the descent over south Peninsula is mainly due of thermal advection (apart from orography). Over south Peninsula at 850mb ω due to thermal and vorticity advection oppose each other. It is generally seen that the ω (due to dynamical forcing) fall off with increasing height. ω due to friction and orography have, of necessity, to fall off with height.

Fig. 7 (a , b) shows the vertical profiles of ω due to various forcings on 7th near centres of ascent and descent. It is seen that the effect of dynamical forcings is larger and they generally fall off with height.

We have averaged the ω (at each latitude and level) between Longs. 55° and 95°E. Fig. 7 (c, d) shows the y-p sections of the zonally averaged ω on 7 July and 19 July. The meridional cell with ascent over north India and descent to the south is clearly seen on 7 July This cell is more marked than in mean July.

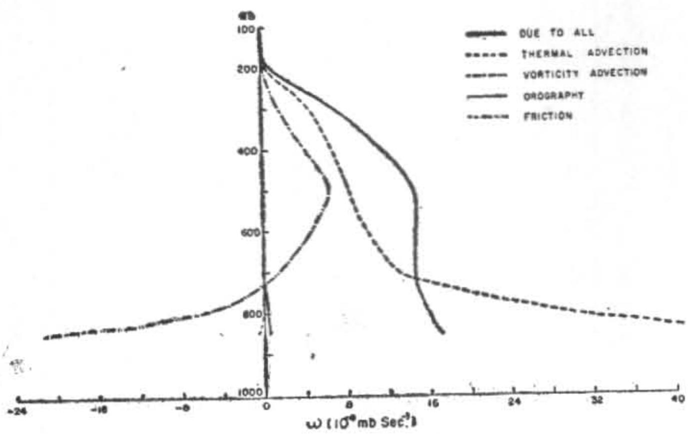


Fig. 7 (a). At 15°N, 77·5°E

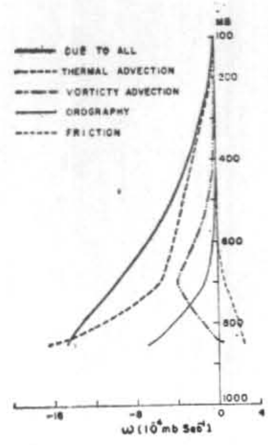


Fig. 7 (b). At 20°N, 72·5 °E

(ω) due to various forcings, 7 July 1963

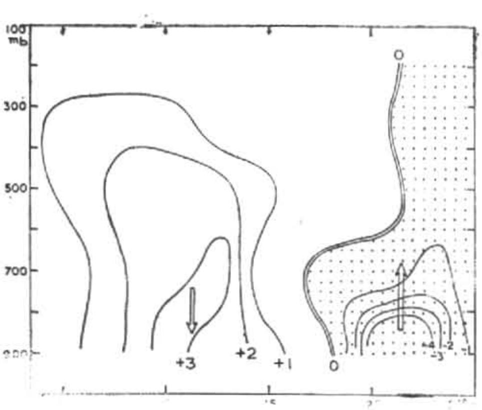


Fig. 7 (c). 7 July

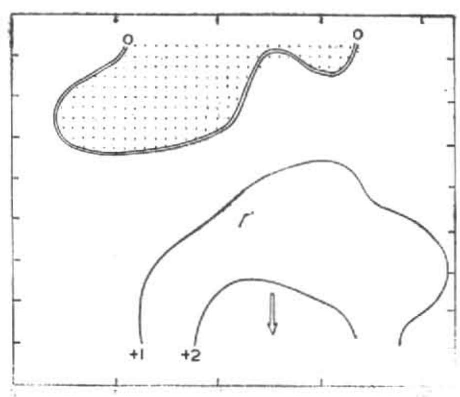


Fig. 7 (d). 19 July 1963

[ω] 10^{-4} mb/sec

On 19 July, however, this meridional cell is not seen and we have uniform descending motion throughout.

We have also computed conversion from potential to kinetic energy associated with the Hadley and Walker circulations (Keshavamurty and Awade 1972).

The conversion from zonal available potential energy into zonal kinetic is given by

$$c\ (A_z,\ K_z)\ =\ -\int \widetilde{[\omega]''\ [\alpha]''}\ \frac{dp}{g}$$

and the energy conversion between eddy available potential energy and eddy kinetic energy is given by

$$c\ (A_E,\ K_E) = -\int \widetilde{[\omega^*,\ \alpha^*]}\ \frac{dp}{g}$$

where

$$\omega\ =\ \frac{dp}{dt}\quad \alpha\ =-\frac{\partial\phi}{\partial p}$$

The square bracket indicates zonal average, the tilde indicates area average and the double prime the deviation from area average. The star represents deviation from zonal average. The energy conversions are (watt/m^2=10^3 sec $^{-3}$ gm) :

	Mean July	7 July (Strong monsoon)	19 July (Weak monsoon)
$Ac\ (A_z,\ K_z)$	0·19watt/m^2	0·57 watt/m^2	+0.06 watt/m^2

It is seen that the climatological meridional monsoon cell is direct (energy production). It is more marked on a day of strong monsoon and the rate of energy production is larger than the mean. On a day of weak monsoon, this meridional cell is not seen and there is mostly descent throughout. The energy conversion is also much less.

We have also computed the conversion between eddy available potential energy and eddy

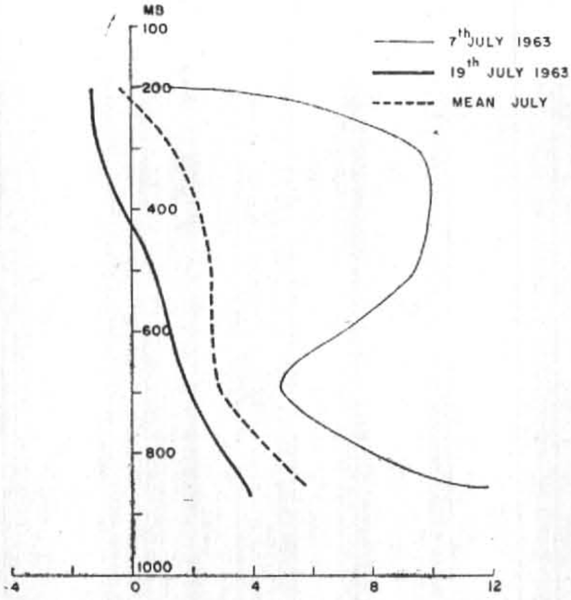
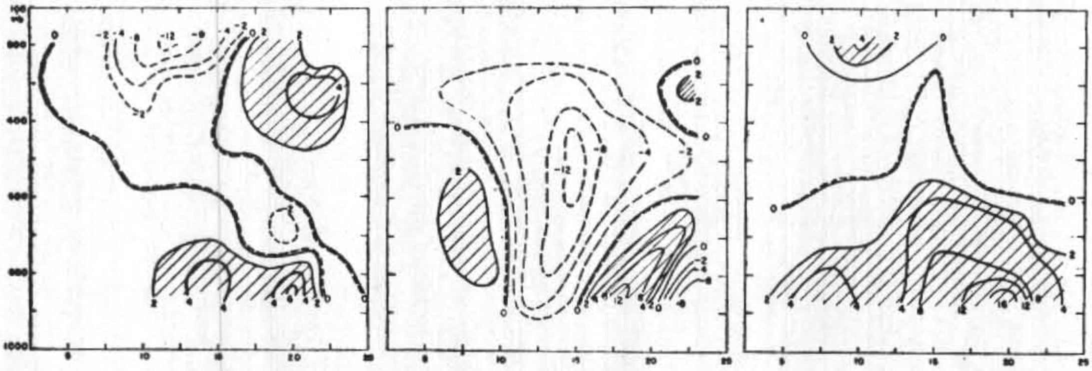


Fig. 8. Values of—[ω]″ [α]″ in units of 10^{-5} m² sec⁻³



(a) Mean July (b) 7 July 1963 (c) 19 July 1963

Fig. 9. Height data—[ω^*, α^*] in units of 10^{-5} m² sec⁻³

kinetic energy on these dates. They are

	7 July	19 July
$C(A_E, K_E)$	$-0{\cdot}08$ watt/m² +	$0{\cdot}12$ watt/m²

Surprisingly there is conversion from eddy available potential energy into eddy kinetic energy on 19 July and *vice versa* on 7 July. The loss of energy by the eddies to the zonal flow on 7 July may be because on this day the monsoon system over western India was tending to weaken.

Fig. 8 shows the vertical profile of energy conversion from A_z to K_z during mean July, on 7 July 1963 and 19 July 1963. It shows that the total energy conversion is much larger on 7 July than in the mean and much smaller than the mean on 19 July 1963, the weak monsoon day.

Fig. 9 (a, b, c) shows y-p sections of energy conversions from A_E to K_E during mean July, 7 July and 19 July respectively. During mean July there are regions of positive and negative conversions so that the net over the whole latitudinal belt becomes small. On 7 July, the strong monsoon day, there is a very large negative conversion (*i.e.*, from K_E to A_E) mainly in the middle troposphere. This is due to the correlation between ω and α around latitude 10° N to 15° N. This gives a net negative conversion over the whole latitudinal belt, on

19 July, however, we have large positive conversion, mainly in the lower troposphere. This gives a net positive conversion.

Because we have used quasi-geostrophic ω and due to the considerable smoothing in the analysis and also due to the absence of latent heat forcing, the energy conversions are under estimated.

The results of the two contrasting situations are tentative. We propose to study more break and active monsoon situations.

5. Concluding remarks

(*i*) Computations using the quasi-geostrophic ω equation gives a smooth, consistent picture of the vertical circulations of the monsoon. The ω-field and the associated energy conversions show large fluctuations (from the mean) during contrasting monsoon epochs.

(*ii*) The meridional circulation is well-marked on the strong monsoon day and there is conversion from ZAPE to ZKE. On the weak monsoon day there is descent throughout and this energy conversion is much smaller.

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