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On the mean meridional circulation during the contrasting periods of normal and below normal monsoon activity

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सार — सामान्य तथा सामान्य से कम मानसूनी क्रियाशीलता की परस्पर विरोधी अवधियों के लिये 80° पूर्व पर माध्य रेखांशिक परिभ्रमण अभिकलित किया गया। तब मालूम हुआ कि मानसून के महीनों में इस क्षेत्र में 35° उ० पर आरोही गति और 15° उ० पर अवरोही गति मिलती है। अक्रियशील मानसून के दौर में 15° उ० पर अवरोही गति मुख्यत: स्थानीय शीतलन की वजह से तीव्र हो जाती है। इस अवरोही गति की क्षतिपूर्ति के लिये भूमध्य रेखीय क्षत्र पर सशक्त आरोही गति दिखाई देती है।

ABSTRACT. For the contrasting periods of normal and below normal monsoon activity, the mean meridional circulation (M.M.C.) over 80 deg. E was computed. It was found that during monsoon months this region is characterized by rising motion over 35 deg. N and sinking motion over 15 deg. N. During a monsoon break period sinking motion over 15 deg. N is intensified mainly due to local cooling. Strong rising motion occurs over equatorial regions to compensate for this sinking motion.

1. Introduction

In an earlier paper by the authors Sankar Rao and Kusuma (1978) experiments were carried out to quantitatively determine the sensitivity of mean-meridional circulation (M.M.C.) to the various input parameters within the framework of Kuo's (1956) model. As a further step, the main aim of the present study is to compute M.M.C. over the Asian region during the periods of contrasting monsoon conditions based on Kuo's (1956) model only. The study of M.M.C. during the break monsoon situation is taken up here as it is pointed out by some synoptic meteorologists, *e.g.*, Ramaswamy (1962), that a drastic change in the general circulation from zonal to Rossby wave regime is noted during the onset of a break. These Rossby waves are found to propagate even upto Indian region during such breaks. Whether a change in the mean conditions allows these waves to amplify or these waves apply brakes to mean conditions is not yet clear. It is well known that these waves have significant effect on the global M.M.C. *via* their large scale eddy stresses and eddy heat transport. Therefore, it is reasonable to hypothesize that the forcings due to the diabatic heating along with the forcings introduced by large scale eddies can influence the monsoon circulation *via* their effect on the Hadley circulation. In computing such variation in the Hadley cell, over a period of few weeks, we need to compute the diabatic heating profiles. This is the most difficult task. As a first step we can think of using empirical methods to compute this forcing due to diabatic heating.

2. Empirical inference of the vertically integrated diabatic heating

It is inferred from the results obtained by Sankar Rao and Kusuma (1978) that the forcing due to heating plays a dominant rôle as far as the tropical Hadley cell is concerned. Both observationally and theoretically the problem of computing the diabatic heating is a formidable one. To infer the vertically integrated diabatic heating, $\bar{Q}_\varphi$, an empirical approach similar to that of Y. Mintz (1958) is adopted here. As a first step, we tried to estimate $\bar{Q}_\varphi$ by an empirical equation :

$$\bar{Q}_\varphi = a(\triangle T - \triangle T_m) + b\,\frac{L}{c_p}(\triangle X - \triangle X_m) + c\,\frac{g}{c_p}(\triangle Z - \triangle Z_m) \qquad (1)$$

Utilizing $\bar{Q}_\varphi$ given by Newell *et al.*(1976) and $\triangle T$, $\triangle T_m$, $\triangle X$, $\triangle X_m$, $\triangle Z$, $\triangle Z_m$, from Oort and Rasmussen (1971), for northern hemispheric (N.H.). Winter and summer seasons at 10 deg. latitude interval, from 0 deg. to 70 deg. N latitude, an overdetermined system of 16 equations was solved by least square method to obtain *a, b,* and *c* as follows :

$a = 27.9$, $b = 10.2$ and $c = 63.3$ Joules m^{-2} sec^{-1} K^{-1}

Eqn. (1) with the above coefficients was tested as follows. At first $\bar{Q}_\varphi$ is reproduced and the results are given in Figs. 1 and 2 for winter and summer respectively,

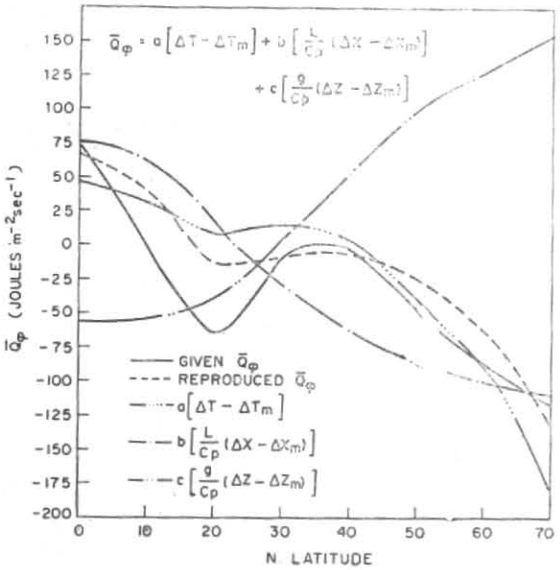


Fig. 1. Diabatic heating in Joules m^{-2} sec^{-1} for winter by least square method

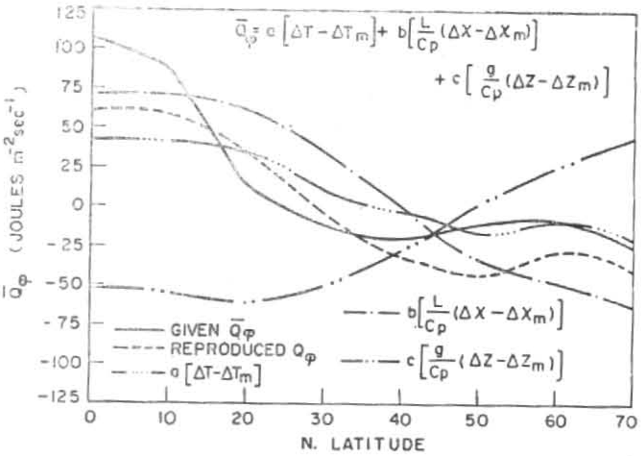


Fig. 2. Diabatic heating in Joules m^{-2} sec^{-1} for summer by least square method

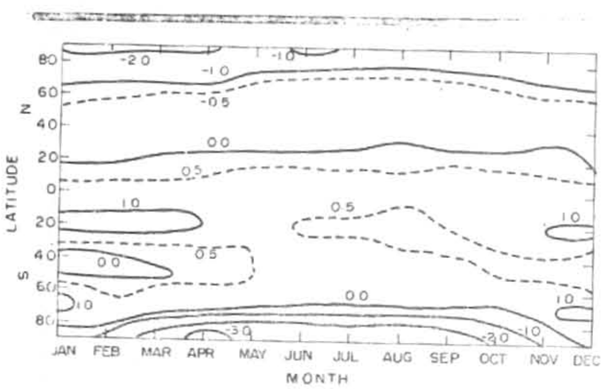


Fig. 3. Zonal mean diabatic heating $\bar{Q}_\varphi$ in 10^2 Joules m^{-2} sec^{-1}

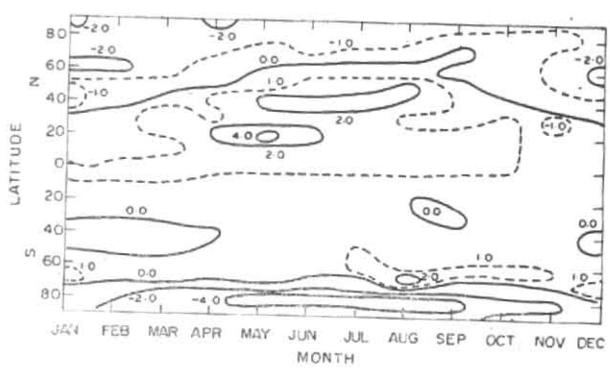
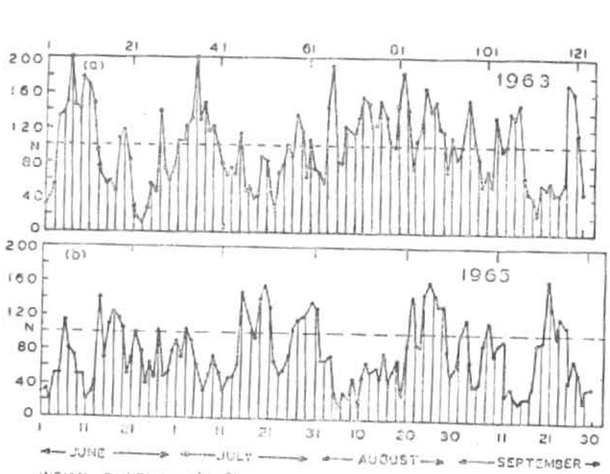


Fig. 4. Diabatic heating $\bar{Q}_\varphi$ for 'normal conditions' in 10^2 Joules m^{-2} sec^{-1}, along 80°E longitude



Figs. 5(a&b). Rainfall activity during (a) 1963 and (b) 1965
[*Courtesy* : R.N. Keshavamurthy *et al.*]

We note the following :

(a) The computed curves show similarity of profile with observations in summer and winter. For instance the double maxima in winter are reproduced.

(b) The maximum percentual deviation in heating magnitudes occurs in tropics in general.

To further test (1), the zonal mean diabatic heating, and the diabatic heating over Asian region (80 ° E) were computed with (1). The zonal mean data (such as $\triangle T$, $\triangle X$,$\triangle Z$, etc) for N.H. up to 70° N were taken from Oort and Rasmussen (1971). For 80° N and 90° N, and also for the Asian region (along 80° E) data published by Direction of Commander, Naval Weather Service Command, were utilised. For the southern hemisphere, both for the zonal mean and Asian region values, data published by U. S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service, were utilised. The results are given in Figs. 3 and 4. We note the following from Fig. 3 which is for zonal mean heating.

(a) In the zonal mean case the southern hemisphere (S.H.) heating seems to be stronger than for N.H. The maximum occurs at about 20 deg. S.

(a) Generally the heating pattern is flat for the northern hemisphere (N.H.).

(c) Strong cooling is indicated at the South Pole.

Fig. 4 which is for Asian region, shows the following interesting features :

(a) A region of maximum heating occurs from 20 to 50 deg. N for months of April to August, the strongest heating occurring at 20 deg. N in May. These months are summer monsoon months for the northern hemisphere during which African and Asian regions get heated.

(b) Comparatively, S.H. heating is weak.

The above tests indicate that the Eqn. (1) is able to reproduce certain basic features in a semi-quantitative sense. Therefore, we decided to use (1), as a beginning, to compute the integrated heating $\overline{Q}_\varphi$ over Asian region for contrasting monsoon periods.

3. M.M.C. over Asian region during contrasting monsoon periods

To obtain the M.M.C. over Asian region we need all the input parameters such as $\overline{Q}_\varphi$, $\overline{v'T'}$, $\overline{v'u'}$, etc, over that region. We considered 80 deg. E as a representative meridian for this purpose. We considered 1963 as a good monsoon year and 1965 as a drought year basing on the general experience and on the studies of Keshavamurthy *et al.* (1972), Figs. 5 (a-b). Especially during August of 1965, there was a long break and the effects of it were felt severely over Indian region.

For actual data during the monsoon periods of these years, 1963 and 1965, over 80 deg. E, the upper air data of the following stations is considered for the months of June to August.

(1) Mys Jelanyia (76° 57′ N, 68° 38′ E), (2) Khanty - Mansi (60° 58′ N, 69° 04′ E), (3) Omosk (54° 56′ N, 73° 24′ E), (4) Karaganda (49° 48′N, 73° 08′ E), (5) Balkash (46° 54′ N, 75° 00′ E), (6) Khorag (37° 30′N, 71° 30′ E), (7) New Delhi (28° 34′ N, 77° 07′ E), (8) Nagpur (21° 06′ N, 79° 03′ E), (9) Bombay Santa (19° 07′N, 72° 51′ E) and (10) Trivandrum (8° 00′N, 77° 00′ E).

The station statistics like $\overline{T}$, $\overline{X}$ and $\overline{Z}$ were interpolated over to a grid with 5 deg. and 100 mb interval.

In order to infer the data for 0 deg. and 5 deg. N, for which there are no stations, Aitken-Neville (1967) iterated interpolation scheme is utilized between 5 deg. S and 15 deg. N, the interpolated values so selected as to hold a similarity for normal conditions for the corresponding period. For 80 deg. N and 85 deg. N, similar procedure was utilised. Here for normal conditions data published by U. S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service were utilised. Diabatic heating profiles for June-August respectively for 1965 and 1963 are shown in Figs. 6(a-c). The most important points that can be inferred from these figures are following :

(a) Maximum heating occurs between 30 deg. N and 40 deg. N, for all periods considered. The profiles of heating show similarity from year to year.

(b) Towards the polar regions the heating is considerably larger for all monsoon months in 1965, when compared to 'normal' or 1963 patterns.

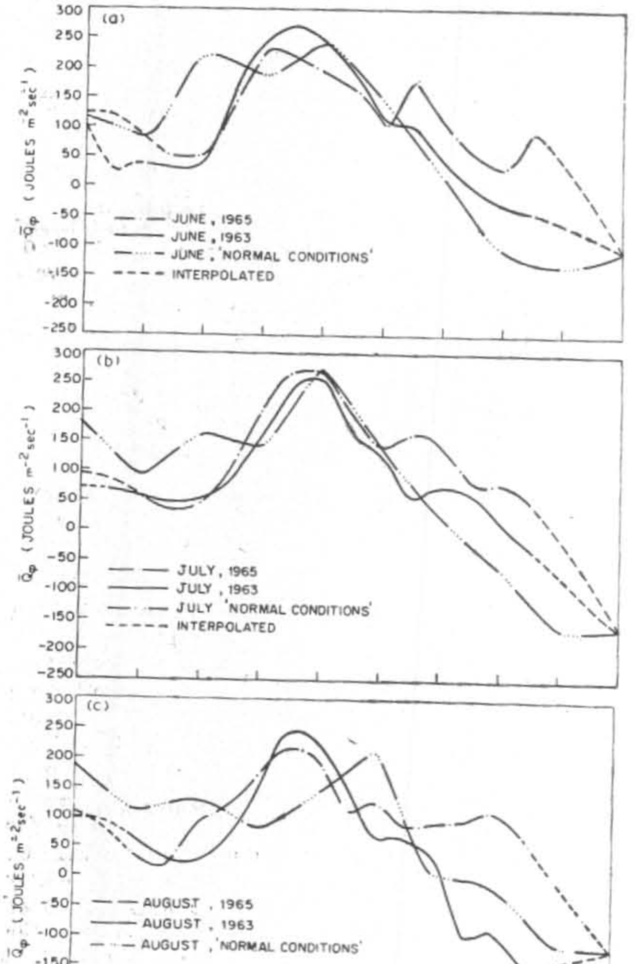
Other statistics such as $\overline{v'T'}$, $\overline{v'u'}$ etc obtained from station data and iterpolated over to the grid used, will not be shown here. Suffice it to say that we checked all the statistics with the existing global statistics and were satisfied with the computed data. For surface stress Hellerman's (1967) data were taken. The vertical distribution of stress and the diabatic heating are the same as assumed in the earlier paper by Sankar Rao and Kusuma (1978). Thus acquiring all the relevant input data for June-August of 1963 and 1965, we computed the M.M.C. over the N.H. along 80 deg. E. The earlier results (Sankar Rao and Kusuma 1978), showed the importance of the S.H. However, there are no station data for the years 1963 and 1965 available. So we are forced to work with N.H. data only. We hoped to get atleast a semi-quantitative picture of the M.M.C. within the framework of Kuo's (1956) model only. The mean-meridional circulation is defined in terms of a stream function ψ as follows :

$$v_1 = \frac{1}{a\cos\varphi}\frac{\partial\psi}{\partial p},\ \omega_1 = -\frac{1}{a\cos\varphi}\frac{\partial\psi}{\partial\eta}$$

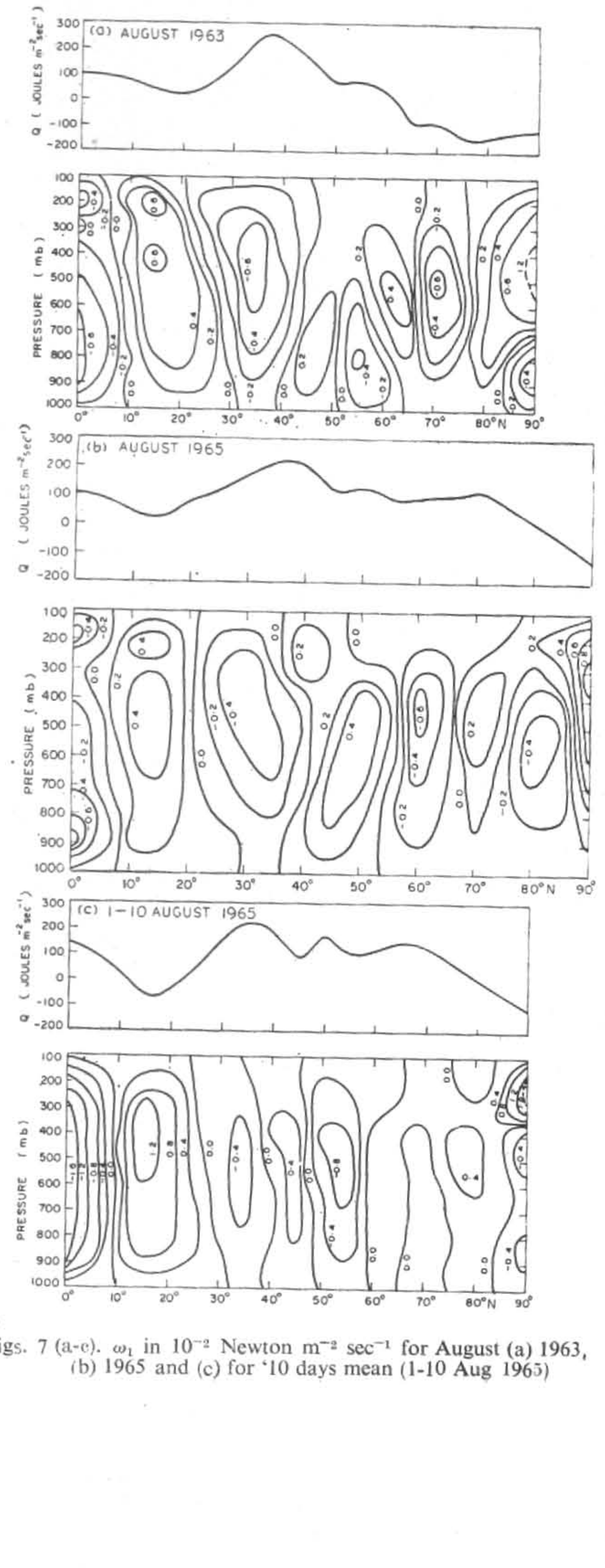
The final governing equation of the model is :

$$\frac{\partial A}{\partial p}\frac{\partial\psi}{\partial p} + \frac{2R}{a^2 p}\frac{\partial T_0}{\partial\eta}\frac{\partial^2\psi}{\partial\eta\,\partial p} + \frac{R}{a^2}\left(\frac{\partial}{\partial p}\frac{1}{p}\frac{\partial T_0}{\partial\eta}\right)\frac{\partial\psi}{\partial\eta}$$

$$-\frac{R\Gamma_0}{a^2 p}\frac{\partial^2\psi}{\partial\eta^2} = \frac{R}{ap}\frac{\partial H}{\partial\eta} + \frac{f}{\cos\varphi}\frac{\partial\chi}{\partial p}$$



Figs. 6 (a-c). Diabatic heating $\overline{Q_{\varphi}}$ in Joules m^{-2} sec^{-1} for (a) June, (b) July and (c) August



Figs. 7 (a-c). ω_1 in 10^{-2} Newton m^{-2} sec^{-1} for August (a) 1963, (b) 1965 and (c) for '10 days mean (1-10 Aug 1965) where, $A = \frac{fz_0 + c^2}{\cos^2 \varphi}$; $\Gamma_0 = \frac{\partial T_0}{\partial p} - \frac{RT_0}{p\, c_p}$

$$\chi = g \frac{\partial \tau_{xz}}{\partial p} + \frac{1}{a \cos^2\varphi} \frac{\partial}{\partial \varphi} \overline{(u' v' \cos^2 \varphi)} + \frac{\partial}{\partial p} \overline{(v'\omega')}$$

$$H = \frac{Q}{c_p} - \frac{1}{a \cos \varphi} \frac{\partial}{\partial \varphi} \overline{(v' T' \cos \varphi)} -$$

$$- \frac{\partial}{\partial p} (\overline{\omega' T'})$$

$$\tau_{xz} = \tau_{x0}\, e^{\beta (p/p_s - 1)}$$

$$Q(\varphi, p) = \left[\frac{g}{p_s} \int_0^{p_s} \left(Q(\varphi, p)\, \frac{dp}{g} \right) \right] F_Q$$

where,

$$F_Q = e^{-\gamma (1 - p/p_s)} \left[c_1 \sin \frac{\pi}{2} \left(1 - \frac{p}{p_s} \right) + c_2 \right]$$

β, γ, c_1, c_2 are constants which can take different values. χ is the momentum forcing whereas H is the forcing due to heating. For the datailed description of the model, the paper by Sankar Rao and Kusuma (1978) can be referred. The final governing equation is solved using the relaxation technique.

ω_1 fields are obtained by such computations for the months of June to August of the drought year 1965 and the normal monsoon year 1963. Figs. 7(a-b) describe the ω_1 fields and the corresponding heating profiles for August 1963 and 1965 respectively. ω_1 fields for the months June and July of the years 1963 and 1965 are not shown here. We notice the following points from such a computation :

(a) The main feature of the M.M.C. for all the months is the strong tropical reverse Hadley cell with rising motion over about 35 deg. N and sinking motion around 15 deg. N. Almost a similar pattern has been obtained by Datta and Mukerji (1975) where they have around 80 deg. E, the region of sinking motion concentrated around 15 deg. N. The sinking motion extends upto 600 mb during the active monsoon period whereas it is upto 200 mb during the break monsoon period. This salient feature that the vertical velocity undergoes a reversal of sign in height during the active monsoon situation noted by Datta and Mukerji (1975) is not inferred in the present study. This could be due to the fact that the model adopted in their study is three dimensional whereas here it is a zonal mean two-dimensional model.

A comparison with the results obtained by Das (1962) based on the ten-lyer, quasi-geostropic adiabatic model is of interest. The results agree only at 900 mb level where the sinking motion is prevailing around 15 deg. N along 80 deg. E longitude. However the most important model difference to be noted is that Das (1962) has computed vertical velocities using the adiabatic assumption whereas in the present study it is the diabatic heating parameter which drives the meridional cell along 80 deg. E with rising limb around 35 deg. N and sinking limb around 15 deg. N. It is the orography that plays an important role in the computations carried out by Das (1962).

(b) The cell seems to be strongest in June.

(c) In June and July of 1963, the middle latitude reverse cell, with rising motion at 65 deg. N and sinking motion over 50 deg. N, is also prominent.

(d) In June 1965 the magnitude of the rising motion over 35 deg. N is significantly weaker than for June 1963.

(e) In July 1965, the sinking motion over 20 deg. N is considerably stronger than in July 1963.

(f) In August 1965 the strength of the rising motion over 30 deg. N is weaker than the 1963 August.

On the whole we can say that there can be significant interannual variations in the sensitive parameter like M.M.C. in this region. Next, it is felt that M.M.C. computation during a break period may be more revealing than the monthly M.M.C's. Therefore, a period of 10 days from 1 to 10 August 1965 was chosen for such computations.

Fig. 7(c) shows the results of such a computation. The corresponding heating profile is shown at the top of the figure. The following can be noted :

(*i*) The rising motion at 35 deg. N is still weaker than for August 1963.

(*ii*) The reverse Hadley circulation with rising motion over about 35 deg. N and very strong sinking motion over about 15 deg. N is still present. The strong sinking motion over 15 deg. N could be due to the strong cooling over 15 deg. N as seen from the heating profile given at the top of the figure. Incidentally, it is the latitude over which the monsoon depressions generally form.

(*iii*) The air is drawn from the equatorial region, but not from the northern rising cell at 35 deg. N to compensate for the sinking motion at 15 deg. N, for the equatorial regions are less stable than the 35 deg. N region in the mean.

4. Conclusions

We express the following conclusions :

(a) The pattern of the M.M.C. over this Asian region considered is mainly governed by the distribution of heating. In general, rising motion prevails over 25 to 40 deg. N latitude belt and sinking motion occurs over 10 to 25 deg. N latitude belt. The exact extent of this sinking cannot be inferred because the data are extrapolated beyond 8 deg. N to the south upto the equator. However, the results can be treated as indicative.

(b) However, the ω-field computed for ten days of break monsoon conditions also shows very much similar pattern as mean August 1963 or 1965. The ony difference being that the descending motion in the belt of 10 to 30 deg. N is more prominent in 10 days mean conditions compared to the monthly mean. The strength of the sinking motion in this belt during 10 days break period is almost double the strength of the sinking motion noted during August 1963.

(c) During a severe break period of 10 days from 1 to 10 August 1965, cooling of the atmosphere seems to be taking place over 15 to 20 deg. N latitude belt, somehow (S.S.T.A.) ? As a result strong downward motion occurs over this region where depressions normally form. Strong compensatory upward motion occurs over the equator. Also, the strong downward motion noticed in the belt from 15 to 20 deg. N during the break may be due to the movement of the monsoon trough from this region which normally stays there, to the foot hills of Himalayas.

(d) In such a large scale situation, the monsoon depressions cannot grow as in normal conditions. Thus the atmosphere is depleted of normal amounts of latent heat release over this region. This might tend to further accentuate the downward motion. Thus the break might be amplifying until something else happens to arrest the trend. It is the general observation of the synoptic meteorologists over this part of the globe that always the monsoon activity is intensified simultaneously with the formation of a low in the Bay. These depressions seem to be the greatest contributors for the normal monsoonal rainfall distribution.

This study has many limitations such as (1) empirical formula for the heating, (2) Rayleigh type of frictional treatment, and (3) exclusion of Walker circulation effects. Therefore, it must be considered only as a first attempt in the study of drought dynamics. We hope to be able to continue these studies on drought dynamics by removing some of the above said limitations in a systematic manner. An attempt is being made to compute large scale vertical velocities over the Asian region based on three-dimensional quasi-geostropical model; the diabatic heating parameter being calculated more physically without allowing for any empericism during the southwest monsoon periods. The problem is challenging and wide open.

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Appendix

List of symbols used

X = coordinate axis directing towards the east

Y = coordinate axis directing towards the north

Z = coordinate axis directing vertically upwards

t = time

λ = longitude

φ = latitude

p = pressure

p_s = surface pressure

u = velocity in λ direction, eastward +ve

v = velocity in φ direction, northward +ve

$\omega = dp/dt$

ω_+ = downward velocity

ω_- = upward velocity

T = absolute temperature

g = acceleration due to gravity

c_p = specific heat at constant pressure

$\bar{D}+D$ = any dependent variable

$$\bar{D} = \frac{1}{A}\int_t^{t+A} D\,dt = \text{time mean of } D$$

A = averaging period

D' = deviation from the time mean

$$D_0 = \frac{1}{2\pi}\int_0^{2\pi} \bar{D}\,d\lambda = \text{latitudinal mean of } \bar{D}$$

χ = humidity mixing ratio and mechanical forcing function

L = latent heat of condensation

$\bar{Q}_\varphi$ = vertically integrated diabatic heating

$Q(\varphi, p)$ = diabatic heating

m = a suffix indicating global mean

$\triangle D = D_{1000} - D_{500}$ = difference between 1000 mb and 500 mb level values of any dependent variable D

τ_{xz} = the frictional stress due to small scale turbulence

β = a constant in $\tau_{xz} = \tau_{xo}\, e^{\beta(p/p_s - 1)}$

γ, c_1, c_2 = constants in F_Q

$$= e^{-\gamma(1-p/p_s)}\left[c_1 \sin\frac{\pi}{2}\left(1-\frac{p}{p_s}\right) + c_2\right]$$

F_Q = a function of p in $Q(\varphi, p)$

$$= \left[\frac{g}{p_s}\int_0^{p_s} Q(\varphi, p)\,\frac{dp}{g}\right] F_Q$$

R=gas constant of air

a=radius of the earth

f=coriolis parameter

Ω=angular velocity of the earth

c=proportionality friction constant

$Z_0 = f - \frac{1}{a \cos \varphi} \frac{\partial (u_0 \cos \varphi)}{\partial \varphi}$ = absolute vorticity

Γ_0=stability parameter