Indian J. Met. Hydrol. Geophys. (1978), **29**, 1 & 2, 219-231

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Large-scale rainfall over India during the summer monsoon and its relation to the lower and upper tropospheric vorticity

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ABSTRACT. The daily variation of the lower and upper tropospheric wind field for the monsoon seasons of 1972 and 1973 is investigated. It is shown that the changes in the large-scale rainfall are directly related to those in the large-scale vorticity above the frictional boundary layer on a day-to-day basis throughout the two seasons, large cyclonic vorticity being associated with active spells and anticyclonic vorticity with weak monsoon spells. In the upper troposphere, the regional average of the anticyclonic vorticity is generally found to increase in active periods, decrease slightly in breaks and spectacularly towards the end of the break and increase again during revival. The maximum value of the kinetic energy of the easterlies during a season is found to occur during the break or weak monsoon spell for the seasons studied. The major difference in the upper tropospheric circulation of the two seasons is in the meridional component which is southerly over large regions over India in 1972 and northerly over the entire region on most days in the season of 1973. The contribution of the meridional advection of vorticity in determining the upper level divergence is found to be significant and its variations are found to be correlated to those of the lower-level convergence.

1. Introduction

We present here the variation of gross features of the upper tropospheric wind and vorticity over India for two monsoon seasons of 1972 and 1973. The aim is to gain a physical insight into the difference in the circulations during a drought season (such as 1972) and a season with above average rainfall (as in 1973). The variation of a crude index of the 900 mb vorticity is also studied.

We found that the large scale rainfall is directly related on a day-to-day basis to the sum of shears of the zonal component of the 900 mb wind at 80°E in the northern belt between 20°N and 28°N and in the southern belt between 12°N and 20°N. The changes in the lower level vorticity during the seasons studied are much larger than those in the upper level vorticity. The kinetic energy of the upper tropospheric easterlies in the season of 1972 was maximum in the break and for the season of 1973 was maximum in the weak monsoon spell. Both these observations are diametrically opposite to the results obtained in the numerically model of Murakami (1974) and Murakami and Friedrich (1974).

In the upper troposphere, the meridional circulation was found to be considerably different in the two seasons being northerly for most of 1973 and southerly over the northern part for most of 1972. This difference implied a significant difference in an appropriate spatial average of meridional advection of the vorticity and hence to the upper level divergence *via* the vorticity equation. It was shown that this spatial average of the meridional advection of the dominant component of vorticity was much larger than the time rate of change of an spatial average of vorticity except for about four days in each season. Further, the magnitude of this advection is found to be directly related to that of the 900 mb vorticity and hence the lower level convergence indicating that the meridional advection is perhaps the most important term for determining the upper level divergence *via* the vorticity equation.

2. Index of the large-scale rainfall

It is necessary to choose an index for the large-scale rainfall of the country as a whole. The large-scale ($\sim$4000 km) atmospheric circulation over the region during the summer monsoon period is generally favourable for the occurrence of large-scale convergence and hence large scale vertical motion. In fact on any day in July-August, which are the main monsoon months, there is some region or the other which receives rain. The actual rainfall on any particular day is caused by disturbances of the synoptic scale ($\sim$500 km) in which are embedded mesoscale ($\sim$100 km) features. The large-scale circulation seems to organize the synoptic scale disturbances such that the rainfall is also characterized by the large-scale circulation. Thus there are epochs when large areas of the country simultaneously experience rainy or dry spells. It is the temporal variation of this large-scale monsoon rainfall which is of interest here.

We have adopted a rainfall index which is taken as the sum of the rainfall reported by all the stations (meteorological observations) over the plains of India normalized by the sum of the average ($\geqslant$40 years) rainfall for those stations for that day. Thus,

$$\text{Rainfall indevx} = \frac{100 \times \Sigma \text{ Rainfall over plains stations for the day}}{\Sigma\text{Normal rainfall over those stations for that day}}$$

The above normalization procedure removes the seasonal variation. The index gives a reasonable measure of the large-scale rainfall and can be readily computed from the data available at the Weather Central of the India Meteorological Department. A spell in which this index is below is 60 considered to be a weak monsoon spell and in which it is above 140 to be a vigorous monsoon pell.

3. Relation between lower-tropospheric vorticity and the large-scale rainfall

The most obvious feature of the lower level circulation which varies with a time scale comparable to that of the large-scale rainfall fluctuations is the position and intensity of the monsoon trough. It is well known that a situation in which the trough is slightly to the south of its normal position with one or two vortices embedded in it, is one which is characterized by a large amount of well-distributed rainfall over the plains; whereas the trough lying near the foot of the Himalayas, *i.e.*, several degrees to the north of its normal position is associated with 'breaks' in the monsoon (Ramamurthy 1969). The intensity of the trough is reflected in the strength of the associated vorticity field.

During an average monsoon season, the lower level vorticity is cyclonic and concentrated in the belt between 20°N and 28°N. The dominant component of this vorticity is the meridional variations of the zonal wind, *viz.*, $\partial u/\partial y$. There is little cyclonic vorticity over the southern Peninsula between 12°N and 20°N. The major fluctuations in the vorticity are also restricted to the northern belt. The vorticity in that belt is high and cyclonic in active monsoon spells and anticyclonic during breaks. This suggests that the meridional shear of the zonal wind in the northern belt is related to rainfall over the plains in normal and extreme situations. We investigate now if such a relationship exists on a day to day basis between the large-scale rainfall in the country as a whole and the 900 mb vorticity, using the data from the 1972 and 1973 seasons.

In order to study the daily fluctuation of the vorticity, we have adopted the following gross measure. We assume that the shear of the zonal wind at 900 mb between 12°N and 20°N along 80°E is a reasonable estimate of the large-scale vorticity over the southern Peninsula. A similar computation taken between 20°N and 28°N is assumed to characterize the large-scale vorticity on the plains of India. The particular longitude (80°E) has been chosen because a large number of upper wind stations are distributed around this longitude. It is also the central meridian of India and thus passes through the major rainfall area of the plateau region.

3.1. *Monsoon season of 1972*

The daily variation of the rainfall index and the shear of the zonal wind are shown in Fig. 1(a & b).

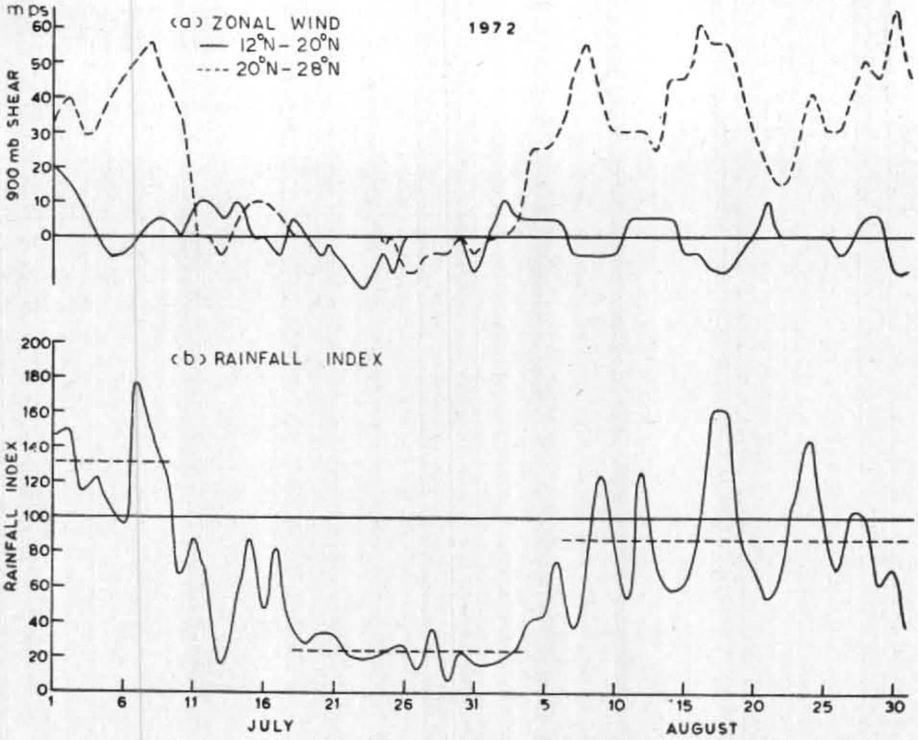

Fig. 1 (a). Daily variation of the difference in the zonal wind component at 900 mb along 80°E between 12°N and 20°N (solid line) and between 20°N and 28°N (dashed line) in m.p.s. for July-August 1972. Positive values imply cyclonic vorticity

(b). Daily variation of the rainfall index for the season of 1972

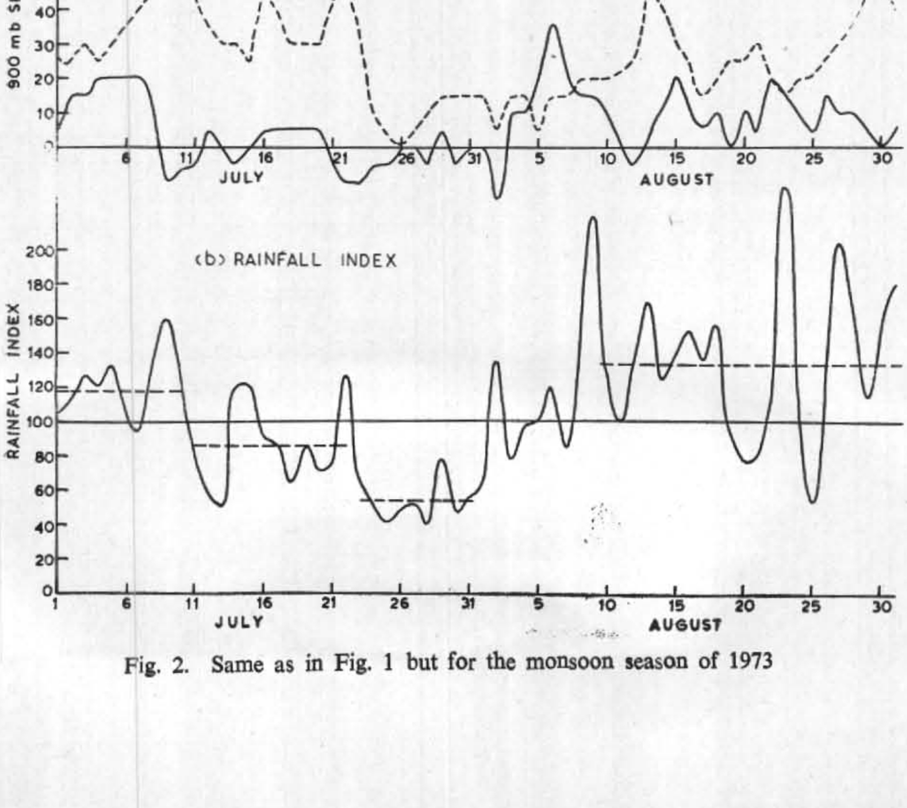

Fig. 2. Same as in Fig. 1 but for the monsoon season of 1973

With the exception of two periods of two-day duration, the variations in the rainfall throughout the season are in phase with those in the shear index of the northern belt, high cyclonic shear being associated with large rainfall index and anti-cyclonic shear with low rainfall index values. In the first exceptional period 11-12 July, normal rainfall was sustained despite vanishing shears and in the second 4-5 August, the rainfall was not high although the shear was cyclonic. Both these reflect the time lag in the transition of the system from active to break situations and break to revival respectively.

3.2. *Monsoon season of 1973*

In contrast to the year 1972, the monsoon season of 1973 was characterized by good large-scale rainfall. Fig. 2(a) shows the daily variations of the rainfall index for this season. The fluctuations of the shears in the northern and southern belt are indicated in Fig. 2(b). The variations of the rainfall are consistent with those of the sum of the northern and southern shears. Unlike the 1972 season, the southern shear contributed significantly during 3-10 August when revival from the weak monsoon spell occurred with the trough moving north across the southern belt.

4. Comparison of some features of the upper tropospheric circulation for the monsoon seasons of 1972 and 1973

In the preceding section, we have seen that the large-scale rainfall is well correlated with the index of the vorticity above the frictional boundary layer not only in the mean but also on a day-to-day basis. Since the atmosphere over India is always conditionally unstable during the monsoon season, this correlation implies that CISK plays an important role in the organization of the large-scale convection. The rainfall in the region of the cyclonic vorticity (*i.e.*, in the region of the monsoon trough and the transient disturbances embedded in it) is usually associated with deep cumulus convection. We, therefore, expect the lower and upper troposphere to be strongly coupled at least in the rainy spells. We have investigated the nature of the upper tropospheric circulation during the various phases of the monsoon in the two seasons of 1972 and 1973 in order to gain some insight into this coupling. Towards this end we have studied the daily variation of various aspects of the zonal circulation, the meridional circulation and the vorticity field.

4.1. *Observations and data processing*

The wind data for 200 mb, 150 mb and 100 mb levels was obtained by analysing the wind field and then picking gridpoint values of the wind vector, from 8°N to 44°N at intervals of 3° for the longitudes 80°E and 90°E. By taking grid values after analysis, the gaps introduced by gaps in observations of the reporting stations were avoided and the smooth data could be readily utilized for computations of derived functions such as the vorticity. At every grid point, the average wind vector for the three levels (100, 150, 200 mb) was computed. The data for this average wind-field represents the mean wind field of the layer in which most of kinetic energy of the zonal flow is concentrated. This averaging filters out the changes in the wind at any level which occur due to variations in the slope of the surface of maximum wind which is embedded in this layer. The layer-mean data was utilized for computations of various functions such as vorticity.

In order to avoid large truncation errors associated with finite difference evaluation of spatial derivatives of the wind field known at this coarse grid, the data was fitted to a sixth order Chebyshev polynomial in the meridional co-ordinate with the min-max approximation (Booth 1958). The root mean square error was of the order of 0·5 m/sec and maximum error at any grid point was of the order of 1·5 m/sec. Further, the position of the cores in the easterly and westerly jets was exactly reproduced in the fitted curves. Using the continuous profiles of the wind field *versus* latitude thus obtained for 80°E and 90°E, daily values of the vorticity, its zonal and meridional advection were computed for the two seasons. In addition, the variation of integral measures of certain features of the circulation such as kinetic energy of easterly and westerly components, vorticity etc obtained by integration over appropriate spatial scales (determined largely by the scale of the regions over which the factor considered has the same sign) are also investigaed.

4.2. *Zonal circulation*

The zonal wind field consists of easterlies south of about 32°N and westerlies to the north. On most occasions the meridional profile of the easterlies

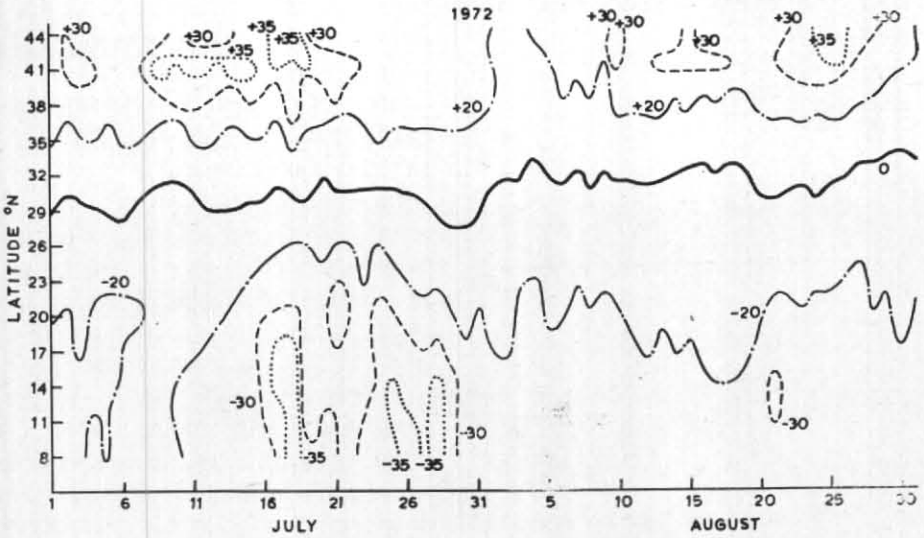

Fig. 3 (a). Daily variation of the meridional profile of the layer-mean (200, 150 and 100 mb) zonal wind component in the upper troposphere in m.p.s. for the monsoon season of 1972

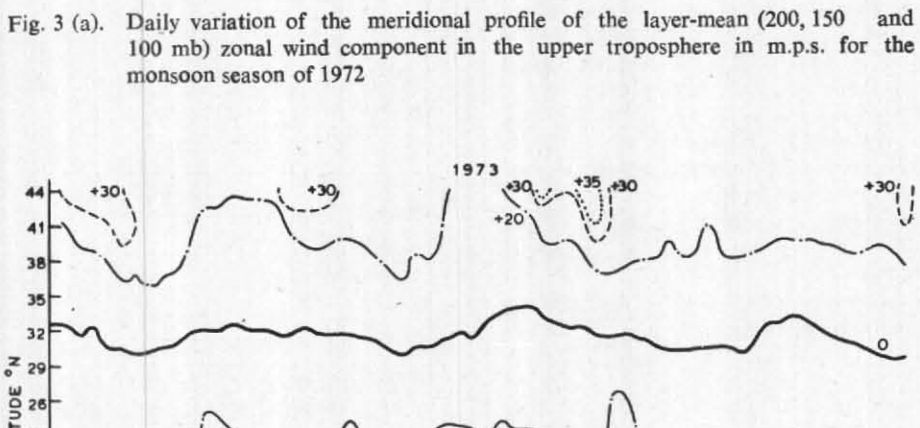

Fig. 3 (b). Same as in (a) but for the monsoon season of 1973

is rather flat south of about 22°N, the vorticity is anticyclonic between this latitude and the latitude of the westerly jet core, being cyclonic north of the latter. On some days the easterlies develop one or two rather weak cores which do not seem to have any significant effect.

Easterlies

The strength of the zonal circulation can be represented by the total kinetic energy of this layer-mean component in the region under investigation. The daily variation of this kinetic energy of the easterly regime along 80°E is shown in Figs. 4, 5 (curve b) for the years 1972, 1973 respectively. The mean kinetic energy for the season of 1972 is smaller than that of 1973 while its variation within the former is much larger than that in the latter.

For the year 1972, it can be seen that the kinetic energy of the easterlies increases rapidly between

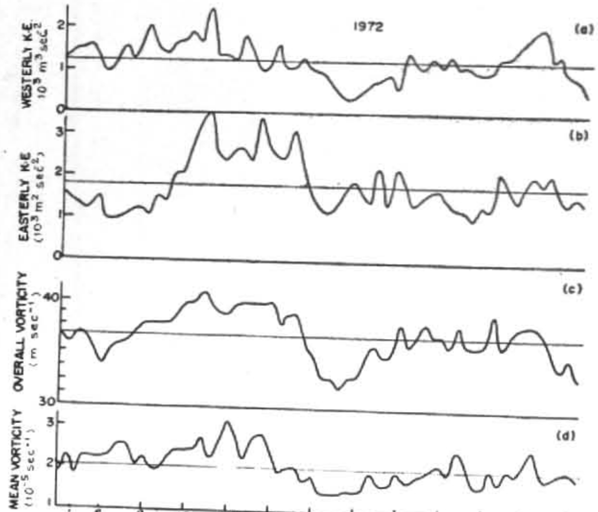

Fig. 4. Daily variation of the following features of the layer mean circulation at 80°E for the region between 8°N and 44°N for the monsoon season of 1972

(a) The kinetic energy of the westerlies over the region in 10^3 m^2 sec^{-2}
(b) The kinetic energy of the easterlies over the region in 10^3 m^2 sec^{-2}
(c) The overall anticyclonic vorticity over the region (*see* text for definition) in units of 10^{-5} sec^{-1}
(d) Mean anticyclonic vorticity (*see* text for definition) in units of 10^{-5} sec^{-1}

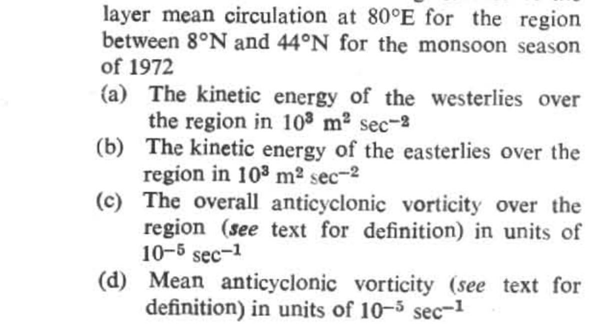

Fig. 5. Same as in Fig. 4 but for the monsoon season of 1973

11 and 17 July, remains large upto 28 July, then decreases sharply upto 1 August. During the months of August it has relatively small fluctuations. We may note that the period of the increase trend (11-17 July) coincides with the period of near normal monsoon. The break monsoon period coincides with the epoch of maximum strength of the easterlies. An inspection of Fig. 3(a) reveals that in this period the kinetic energy of the easterlies has increased at every point, the region of the easterly regime has not increased significantly and there is no prominent core in the profile. The sharp decline in this strength occurs towards the end of the break. The most striking feature of the variation for the season of 1972 is therefore, the high value of kinetic energy attained at the beginning of the break. Its persistence for about two weeks and its sharp decline just before the end of the break. The fluctuations in the cyclonic vorticity associated with cores in the easterlies seem to occur independently of those in the lower level vorticity.

For the season of 1973, Fig. 5 (curve b), the amplitude of the long period oscillation in the kinetic energy is seen to be much smaller than that of 1972. In this year, too, the kinetic energy remains well above the season's mean in the weak monsoon spell and declines sharply towards the end of this spell.

Westerlies

The daily variation of the kinetic energy of the westerlies along 80°E over this region is shown in Figs. 4 and 5 (curve a) for the two seasons. The mean westerly kinetic energy for the 1972 season is larger than the mean for the 1973 season. For 1972, this kinetic energy exhibits an increasing trend from 7 July to 18 July, followed by decreasing trend from 18 July to 3 August. This decreasing trend was found to be more marked for the westerly kinetic energy for 200 mb. The period of this decreasing trend is seen to be identical with that of the break monsoon. Thus we see that at the beginning of the break the westerlies were at their strongest, attaining a core of about 35-40 mps near 41°N with a trough to the west of our reference longitude 80°E. At this time the kinetic energy of the easterlies was also maximum. The westerly kinetic energy increased in the revival period upto 10 August and remained more or less steady from 10 to 20 August. Strengthening of the westerlies between 20 to 26 August and their subsequent weakening does not seem to be related to the large scale rainfall in this period.

The prominent feature of the variation of the westerly kinetic energy for the season of 1972

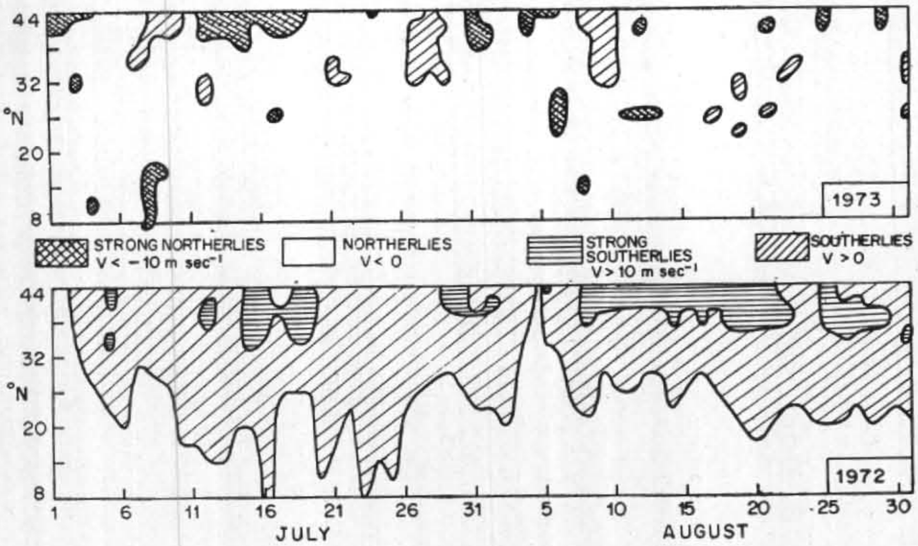

Fig. 6. The upper tropospheric meridional component over the region for the two seasons

(Fig. 5, curve a) is an almost uniform long-period oscillation with a period of roughly 15 days, from the beginning of July to 10 August. This oscillation seems to bear no obvious relationship to the variations of the large-scale rainfall in this period. In particular, the kinetic energy of the westerlies was not high before the beginning of the weak monsoon spell. However we may note that a decrease in this kinetic energy did occur towards the end of the weak monsoon spell and the subsequent increase again coincided with the period of revival.

4.3. *Meridional circulation*

The meridional component at 80°E between 8°N and 44°N for the two seasons is shown in Fig. 6. It is seen that there is considerable difference between the meridional circulation in the two seasons. For the 1972 season, the meridional component is southerly in the northern part of the region except for about four days in July and August at 80°E as well as 90°E. In the near-normal monsoon phase in 10-17 July, southerlies increase in strength in the northern part and extend upto and south of 20°N. During the first part of the break (18-26 July) the meridional circulation is southerly over the entire region. From 26 July when the first signs of revival appeared in the lower-level as the amplitudes of the positive pressure departure decreased, the southerlies receded from the southern portion but remained north of 26°N throughout the season.

For the 1973 season, on the other hand, the meridional component was northerly over most of the region on majority of days. Even when southerlies occurred, their latitudinal extent and temporal persistence was much smaller than that of the 1972 season. The northerlies were strong in the entire belt, attaining velocities larger than 10 m/sec in the northern as well as southern portions. It is important to note that from the view point of the meridional circulation the whole of the 1972 season was markedly different from the 1973 season. The seasonal mean profiles at 80°E for the two years are shown in Fig. 7 along with the long term mean given by Newell *et al.* (1972).

It is necessary to take this kind of variation between two years into account before conditions associated with active and weak spells of the monsoon can be superposed as is traditionally done (Ramamurthy 1969). We consider next the implications of the differences in the circulation between and within different phases of the two seasons for quantities which directly affect the upper level divergence such as the vorticity.

4.4. *Vorticity*

Using the data for 80°E and 90°E we computed the daily values of the relative vorticity and ab-

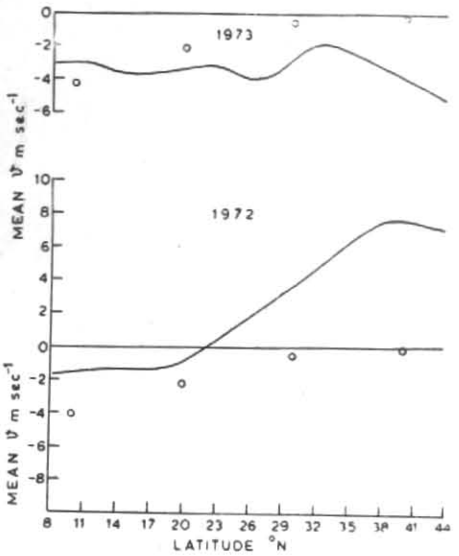

Fig. 7. Mean meridional profile of the layer-mean meridional wind velocity in the upper troposphere at 80°E for the monsoon seasons of 1972 & 1973. The normal values of this component from Newell *et al.* (loc. cit.) are shown as points.

solute vorticity and the advection of one component of the vorticity, *viz.*, $\partial u/\partial y$, at all the grid points. It was found that the calculated absolute vorticity was positive throughout and that the dominant component of the relative vorticity was the meridional variation of the zonal wind $\partial u/\partial y$. In the absence of data on the vertical advection of vorticity, it was not possible to compute the total change in vorticity. Since this vertical advection plays an important role in determining the upper-level divergence, particularly in the large-scale convective regime of the monsoon region, we found that it was not possible to obtain a balance in the vorticity equation when it was neglected (*see* also Holton and Colton 1972). In view of this, an analysis of the variation of spatial average of certain features of the circulation such as the time rate of change and advection of the dominant component of vorticity (*i.e.*, the sum of the planetary vorticity and the meridional shear of the zonal flow) was carried out. In what follows the relative vorticity is estimated by the shear of the zonal flow.

We note that over the latitudinal belt investigated on any day, a large continuous region of anticyclonic shear separates the much smaller regions of cyclonic shear to the north and south. An integral measure of the anticyclonic shear over the region can thus be obtained by summing the shear over all the points with anticyclonic shear. This measure, termed as the overall vorticity from now on, depends upon the strength at any point as well as the region over which the anticyclonic shear extends. The variation of this overall anticyclonic vorticity for the two seasons is shown in Figs. 4 and 5 (curves c). The average strength of the anticyclonic vorticity over the region is estimated by dividing the overall anticyclonic vorticity by the number of points contributing to it. The variation of this mean anticyclonic vorticity is depicted in curves d of Figs. 4 and 5 for the two seasons. Note that a change in overall anticyclonic vorticity can be brought either by local changes, *i.e.*, change in the mean strength or by a change in the extent of the region over which the anticyclonic vorticity prevails. During the season of 1972 the mean and overall vorticity tend to increase during active periods, attain a maximum at the beginning of the break, decrease slightly during and spectacularly towards the end of the break, and increase again with the revival. The variations in the overall vorticity are in phase with those in the easterly kinetic energy during the entire season.

During the season of 1973 also, the overall and mean vorticity showed an increasing trend during active periods, attained a high value before the weak monsoon spell, decreased sharply towards the end of this spell and picked up with the revival of the normal monsoon. The variations of the overall vorticity during 1973 were in phase with those of the westerly kinetic energy.

In summary, our analysis suggests that the overall and the mean anticyclonic vorticity increase during active spells, decrease in the break and decrease spectacularly towards the end of the break.

4.5. *Meridional advection of vorticity*

The marked difference in the meridional circulation in the two seasons results in a difference in the meridional advection of vorticity into the region. In Fig. 8 the regions of positive and negative meridional advection of vorticity, *viz.*, $(\beta - \partial^2 u/\partial y^2)v$, are indicated. Note that from the vorticity equation, a positive (negative) advection implies a decrease (increase) in the upper level divergence. Since we expect strong upper-level divergence to be associated with strong low-level convergence and hence favourable conditions,

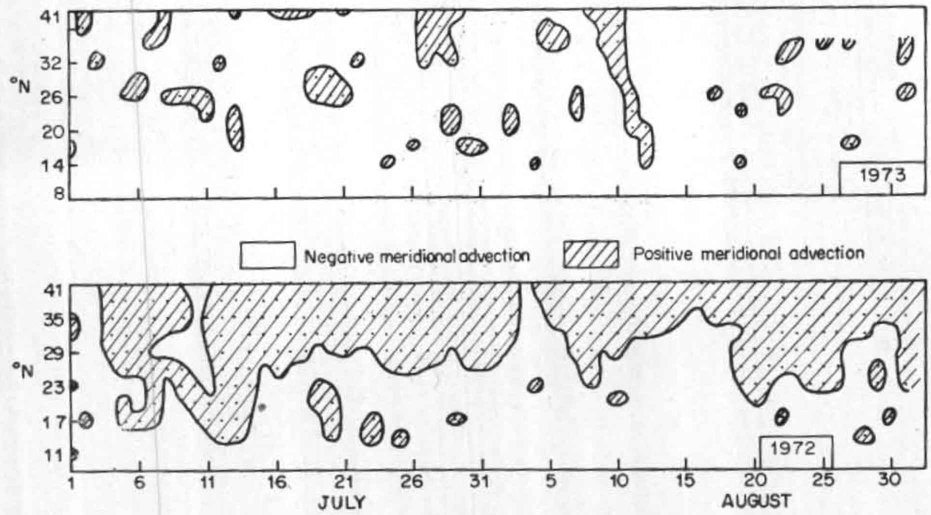

Fig. 8. The regions of positive and negative meridional advection, *i.e.*, $v(\beta - u_{yy})$ for the seasons of 1972 & 1973

positive advection can be considered as an unfavourable element.

In the season of 1972, the meridional advection is seen to be unfavourable north of about 20°N for a vast majority of the days. In contrast, the advection is favourable over most of the region for most of the days for the season of 1973. On any day in the 1972 summer, the positive (or negative) advection regime occupies a large continuous areas, and hence an integral measure for positive (or negative) advection can be obtained by summing the advection over all points at which it is positive (or negative). The variations of such indices of positive or unfavourable and negative or favourable advection for the 1972 season are shown in Fig. 9. It is seen that the favourable component is significant in the first active spell (1-10 July), becomes negligible from 11 to 26 July (with the exception of three days in the beginning of the break), picks up in the first week of August, becoming large from 10 to 20 August and remains non-zero after that. This reflects the contribution of this term to the divergence over the southern portion where the advection is negative. In the northern part, the positive advection is significant from 5 July, becomes very high in the break, decrease sharply towards the end of the break and is large again in the last three weeks of August. Thus the advection is unfavourable in the northern region over most of the season and favourable during active phases only in the southern region.

In 1973, the advection is favourable over the entire season with the exception of about four days and this favourable advection is associated with good rainfall conditions.

5. Interpretation of the observed variations

The variations in the rainfall occur in association with those in the lower tropospheric convergence which in turn depends upon the vorticity above the frictional boundary layer. We expect the variations in the lower tropospheric convergence to be linked to those in the upper tropospheric divergence. This divergence cannot be obtained directly since the grid in the zonal direction is very large and the variation of the zonal wind in this direction cannot be estimated accurately. However, the divergence can be estimated through the vorticity equation. Neglecting the twisting terms, which are not likely to be important and cannot be estimated any way, the vorticity equation in the usual notation with the x-axis pointing eastward, y northward and z vertically upward is

$$\eta_t + \overline{V}.\overline{\nabla}\eta = -\eta\,\overline{\nabla}.\overline{V}$$

where η is the absolute vorticity. Using our observation that the dominant component of the relative vorticity is u_y, the vorticity η will be taken as the sum of the planetary vorticity and this component. Further, since the time and space grid are large, each of the terms will be taken as

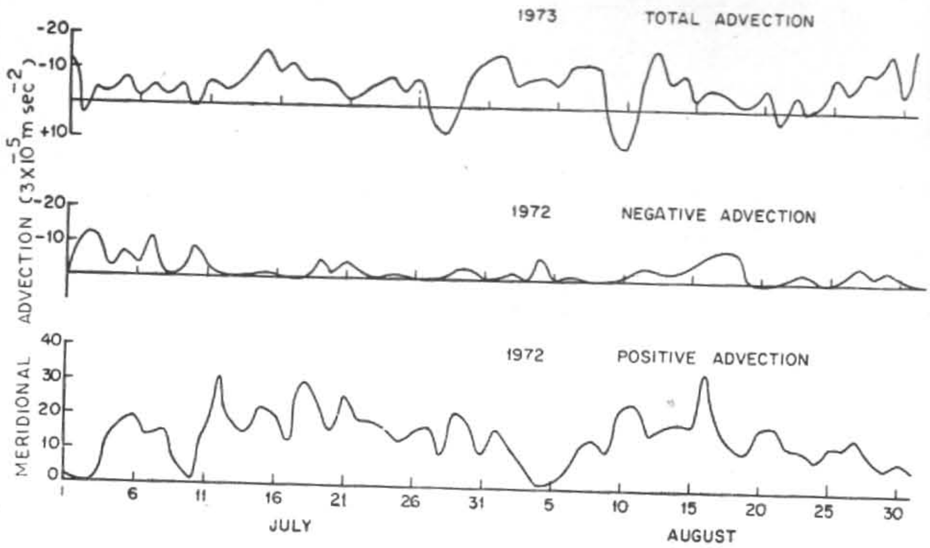

Fig. 9. Daily variation of integral measures of the positive and negative meridional advections over the northern and southern regions in the 1972 season and of the negative advection over the entire belt for the 1973 season in units of 3×10^{-5} m sec^{-2}

appropriate spatial averages and thus a spatial average of the divergence will be deduced. The terms are evaluated as follows.

The first term η_t will be estimated from a smooth curve fitted to the variation of the overall vorticity. In the advection terms, the term $u\eta_x$ cannot be estimated because of the paucity of stations in the southern part over 90°E and hence will not be considered. The meridional advection $v\eta_y$ can be evaluated quite accurately at every latitude since the daily profile $u(y)$ is available from the fitted curve. An integral measure of positive and negative advection defined in Sec. 4.5 is then used to estimate the daily advection. Finally only the sign of the term $w\eta_z$ can be estimated for the active and weak spells. We can thus estimate the contribution of each of the terms to the changes in the divergence.

In the vertical advection $w\eta_z$, the sign of η_z remains the same throughout the season as the vorticity decreases uniformly with height

$$\eta_z < 0$$

The vertical component of velocity is upward in the active spells and becomes downward in the weak spells or breaks (Sikka and Ananthakrishnan 1974). The magnitude of the vertical velocity is expected to be large in active phases and small in breaks (Charney 1963).

Therefore,

$$(w\eta_z)_{\text{active}} < 0$$

$$(w\eta_z)_{\text{break}} > 0$$

and the contribution of the vertical advection implies a large divergence in active phases and a small convergence in breaks and is in phase with the changes in the lower-level convergence.

It was shown that the meridional advection is favourable (implying divergence) over the entire 1973 season and over the southern region over a major part of the 1972 season. For the 1972 season, Fig. 10 depicts the daily variation of the spatial average of meridional advection in the southern region (where it is favourable) along with the variation of an estimate of the time rate of change of vorticity (both in units of 10^{-5} m sec^{-1}). It is seen that the contribution of the meridional advection dominates that of the temporal change except for two brief spells, one before the break and one during the revival. A comparison of the variation of the sum of the two terms η_t and $v\eta_y$ with that of the 900 mb vorticity (Fig. 10) indicates that the two are correlated and hence that the former may provide a reasonable index of the upper level divergence.

For the 1973 season, the meridional advection is much larger than the temporal change in vorticity and is favourable throughout the season. The variation of these two terms as well as that of the

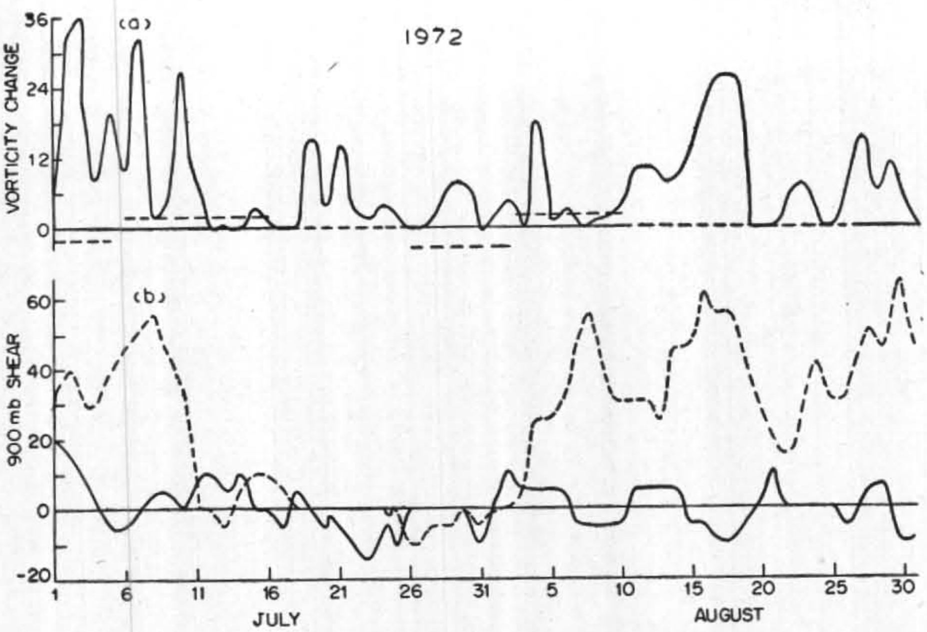

Fig. 10. (a) Daily variation of the integral measure of negative (favourable) meridional advection (solid line) and the contribution of the time-rate of change of vorticity (dashed line) and (b) of the vorticity at 900 mb for the 1972 season

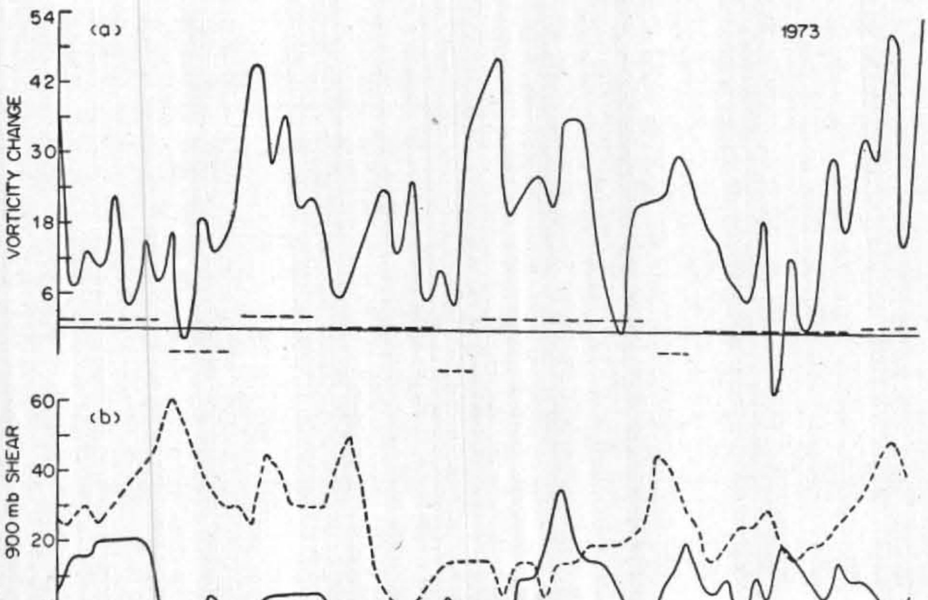

Fig. 11. Same as in Fig. 10 but for 1973 season

900 mb vorticity during the 1973 season is shown in Fig. 11. The advection is again seen to be correlated to the 900 mb vorticity and hence the lower tropospheric convergence.

6. Summary and conclusions

The major results of our study are :

(1) The large-scale rainfall is directly related to the large-scale shear calculated from winds just above the frictional boundary layer on a day to day basis throughout the period July-August. Keshavamurthy (1971) has also obtained a similar result for the rainfall over central India and the vorticity east of 80°E.

(2) The magnitudes of the changes in the lower level vorticity are much larger than those in the upper level vorticity between different spells of the monsoon. Whereas the lower-level vorticity actually becomes anticyclonic during the break, the upper level vorticity remains anticyclonic throughout.

(3) In general, the anticyclonic vorticity in the upper troposphere increases during the active spells, decreases slightly in the weak phases and during the break, and decreases spectacularly towards the end of the break. Note that this change in anticyclonic vorticity can be brought about either by a change in the strength of the easterlies or westerlies or both. The magnitude of the changes in the vorticity over one day suggest that it is necessary to get data over much smaller intervals to make reasonable estimates of the rate of change.

(4) The kinetic energy of the upper tropospheric easterlies in the season of 1972 was maximum in the break and in the season of 1973 was maximum in the weak monsoon spell.

(5) The meridional circulation in the upper troposphere is considerably different for the two years studied; being southerly over large areas throughout the drought season of 1972 and northerly over most of the region throughout the 1973 season.

(6) Integration of the meridional advection of the dominant component of planetary vorticity over appropriate regions indicates that the contribution of this term is larger than that of the temporal variation of the overall vorticity over a majority of days.

(7) A sum of the integral measure of negative meridional advection (*i.e.*, implying contribution to divergence and hence favourable) and the temporal rate of a spatial average of vorticity are found to be well correlated with the 900 mb vorticity and hence the lower tropospheric convergence, particularly for the 1972 season.

These results suggest that the meridional advection of vorticity in the upper troposphere plays a crucial role in determining the divergence and hence the extent to which the upper troposphere is favourable to active rainfall conditions. The meridional circulation and the meridional curvature of the zonal wind together determine the meridional advection. Thus we expect the details of the meridional profile of the zonal wind, such as position, strength of cores, to be important mainly through their influence on u_{yy}. The difference in the meridional component between the two seasons as a whole suggests that circulation associated with active and weak spells of different years cannot be superposed to determine the special features associated with these.

We must emphasize, however, that there are two major drawbacks to this study. The first is a relatively minor one, namely, that we have studied only two monsoon seasons and hence the conclusions derived here will have to be verified by investigation of more monsoon seasons. The second drawback is essentially the local nature of this investigation, since detailed temporal variations of many features of the upper tropospheric circulation along only one longitude are studied in relation to variations in the large-scale rainfall over India. As such it should be considered as complementary to global studies of the tropical circulation such as Krishnamurthy (1971).

It may be worthwhile to compare our observations with the results obtained by Murakami (1974) and Murakami and Friedrich (1974) from a numerical model in which the latent heat due to rainfall was modelled by a heat source. Their results differ from those of our observational study mainly in the following aspects :

(1) The changes in the upper troposphere which occur as a response to the variation in the heat source in their level are much larger than those in

the lower troposphere. The opposite result holds for our observations.

(2) The strength of the easterlies in their model is directly proportional to that of the heat source and hence of the rainfall. However, our study shows that the easterlies attained their maximum strength during the break in the monsoon season of 1972 and weak monsoon spell of 1973.

It is important to note, however, that Murakami (1974) and Murakami and Friedrich (1974) have investigated the variation in the circulations for fluctuations in the large-scale rainfall in a particular region of the spectrum, *viz*., with periods of 12 to 16 days whereas our observational study utilizes unfiltered data. Furthermore, the fluctuations in the rainfall investigated by using the numerical model are of small amplitude and hence the variation in the circulation between weak and active monsoon spells is also of small amplitude. The circulation in the weak monsoon spells of their investigation differs from that observed during prolonged breaks in important aspects.

Thus, for example, the large-scale vertical velocity over the Indian region still remained upward (although reduced in magnitude) and the lower level vorticity remained cyclonic in the weak monsoon spell in their model whereas the lower level vorticity is observed to be anticyclonic and the vertical velocity is expected to be downward in prolonged breaks which are dominated by large-scale anticyclonic vorticity in the lower troposphere accompanied by relatively cloud-free skies and/or shallow convection. For these reasons, a detailed comparison of the results of their model and an observational study such as ours may not be justified.

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