Momentum transport of wave zero during March: A possible predictor for the Indian summer monsoon

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Analysis of monthly momentum transport of zonal waves at 850 hPa for the period 1979 to 1993, between 30°S and 30°N for January to April, using zonal (u) and meridional (v) components of wind taken from the ECMWF reanalysis field, shows a positive correlation (.1% level of significance) between the Indian summer monsoon rainfall (June through September) and the momentum transport of wave zero TM(0) over latitudinal belt between 25°S and 5°N (LB) during March. Northward (Southward) TM(0) observed in March over LB subsequently leads to a good (drought) monsoon season over India which is found to be true even when the year is marked with the El-Nino event. Similarly a strong westerly zone in the Indian Ocean during March, indicates a good monsoon season for the country, even if the year is marked with El-Nino. The study thus suggests two predictors, TM(0) over LB and the strength of westerly zone in the Indian Ocean during March.

1. Introduction

Many workers have studied contrasting features of the energetics of zonal waves during drought and normal monsoon season. Krishnamurti and Kanamitsu (1981) showed that wave 3 lost kinetic energy to zonal mean flow during normal monsoon season and received kinetic energy from zonal mean flow during drought monsoon season. Bawiskar *et al* (1989) showed that small scale eddies were intense during normal monsoon seasons as compared to drought monsoon seasons. The studies of Awade and Bawiskar (1982); Awade *et al* (1982, 1985); Bawiskar and Singh (1992) clearly indicate that the energetics of zonal waves (particularly long waves) influence Indian summer monsoon on a seasonal scale. Momentum transport is one of the properties of zonal waves. It has received considerable attention, as it is a measure of mass transport. The transport of momentum from southern latitudes (as observed during pre monsoon and monsoon months) is associated with the transport of warm and moist air mass. Larger the transport better

is the rainfall. There are a number of studies supporting the statement. Awade *et al* (1985) showed that there is a large northward transport of momentum during normal monsoon season as compared to drought monsoon season. Bawiskar *et al* (1989) showed that the northward momentum transport by wave one is four times larger during normal monsoon years as compared to drought monsoon years. Bawiskar *et al* (1999) have shown that transport of westerly momentum (TM) of waves 0, 1 and 2 have significant correlation with all Indian monsoon rainfall (June to September) on a weekly scale. Though these studies are diagnostic in nature, they clearly indicate that there is a direct relation between momentum transport and performance of monsoon on a seasonal scale and intra-seasonal scale.

In the present study, monthly momentum transport (TM) of zonal waves during January to April at 850 hPa is computed for 15 years (1979–1993) and a correlation analysis between TM and Indian monsoon rainfall (IMR) is performed to see how far TM could be used as a predictor of IMR.

Keywords. Momentum transport; zonal waves; zone of westerlies; Indian monsoon rainfall.
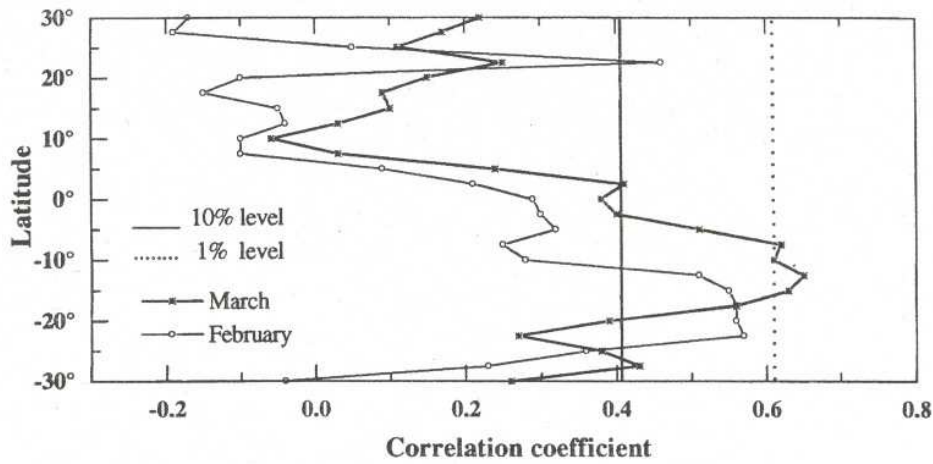
Figure 1. Latitudinal variation of correlation coefficient between momentum transport (m^2s^{-2}) of wave zero at 850 hPa and all-India monsoon rainfall (June to September).

2. Data and methodology

Ten-day mean u and v data between latitudes 30°S and 30°N at 850 hPa for 15 years (1979 to 1993) are taken from the ECMWF reanalysis fields. The data are at 2.5° × 2.5° lat/long interval. The monthly mean of u and v is computed from the ten-day mean data. Fourier analysis has been used to compute monthly TM of zonal waves at 850 hPa from January to April for the period 1979 to 1993 using the relation

$$TM(n) = 1/2(a_n c_n + b_n d_n), n = 1, 2, \ldots\ldots.10,$$
$$TM(0) = 1/4(a_0 c_0), \tag{1}$$

where, n is wavenumber, (a_n, b_n) and (c_n, d_n) are Fourier coefficients of u and v respectively.

TM(0) is momentum transport of wave zero (i.e., zonal mean flow). All India monsoon rainfall (June to September) for 1979 to 1993 is taken from Parthasarathy *et al* (1994).

3. Results and discussion

The TM so computed is correlated with IMR of corresponding years. The results of the correlation analysis indicate that except for wave zero other waves do not have significant correlation. As such, we present and discuss TM of wave zero only.

Figure 1 gives the latitudinal variation of Correlation Coefficient (CC) between TM(0) and IMR for February and March. The CCs for other months are not presented, as they are not significant. In

Table 1. Momentum transport $(m^2 s^{-2})$ of wave zero for the month of March at 850 hPa averaged over 25° S to 5° N and all-India monsoon rainfall (June to September).

Years	Northward TM in March TM(0)	IMR(mm)	Years	Southward TM in March TM(0)	IMR(mm)
1980	.47	882.8	1979	−.02	707.8
1981	.45	852.2	**1982**	−.46	735.4
1983	.43	955.7	1986	−.20	743.0
1984	.65	836.7	**1987**	−.14	697.3
1985	.38	759.8			
1988	.69	961.5			
1989	.94	866.7			
1990	.54	908.7			
1991	.74	784.6			
1992	.35	784.9			
1993	.27	896.7			
Mean	.34	824.9			
S.D.	.39	87.1			
Correlation coefficient		0.73			

The mean, SD and CC are based on 15-years of TM(0) and IMR. The bold years indicate El Nino years.

February, the CC in the region between 25°S and 10°S crosses the line of 10% level of significance. During March, the region of significant CC not only widens up to 5°N but also crosses the line of 1% level of significance. We, therefore, concentrate our discussion on TM(0) for the month of March over the region from 25°S to 5°N (LB).

The latitudinal average of TM(0) over 25°S to 5°N (LB) during March is found to be more significantly correlated with IMR. The CC between TM(0) over LB and IMR is .73 which is almost significant at .1% level of significance. Table 1 gives the all-India seasonal rainfall (June through September) for 1979 through 1993 along with the momentum transport of wave zero for the month of March averaged over LB. For better comparison of TM(0) over LB and IMR, both the series in table 1 are normalized and presented in figure 2. The years of positive (northward) momentum transport and the years of negative (southward) momentum transport are listed separately in table 1 along with 15 years mean and standard deviation (SD) of TM(0) and IMR. The years 1979 and 1987 were drought years and the years 1982 and 1986 were deficient rainfall years. These years fall in the southward momentum category. The remaining years, having good rainfall activity, are associated with northward momentum transport. It may be inferred that the northward momentum transport of wave zero in March leads to a better monsoon rainfall season whereas the southward momentum transport leads to a drought condition or deficient monsoon rainfall season. Asnani and Awade (1978) have also found that northward (southward) momentum transport at 300 hPa by waves 1–4, during April and May, leads to normal (drought) monsoon season over India. Our study shows a similar result for larger data set and at lower troposphere for wave number 0.

Another interesting aspect of table 1 is about the years associated with El-Nino events. Generally failure of Indian monsoon is expected during the El-Nino years. During El-Nino years 1982 and 1987 the Indian region experienced failure of monsoon. However, during prolonged 1991–1994 El-Nino episode the Indian region did not experience a single drought. Table 1 shows that during El-Nino years 1991–1993 (non-failure of monsoon), TM(0) is positive (northward), while during El-Nino years 1982 and 1987 (failure of monsoon), TM(0) is negative (southward). In short, we find that northward (southward) transport of momentum by TM(0) over LB in March subsequently leads to normal (drought) seasons over India even if the year is associated with El-Nino event.

The significant correlation between any two series is either due to a common factor influencing both the series or due to some kind of relation between them. To identify the cause of the significance of correlation between TM(0) and IMR, we examined the spatial distribution of mean (1979–1993) zonal wind component ($< u >$) as it dominates the momentum transport processes. Figure 3 gives $< u >$-field for the month of February and March. A zone of westerlies (shaded) is seen around 10°S which extends from 40°E to 180°E. In March the zone of westerlies weakens and splits into two parts and moves northward up to 5°S. Barnett (1983) also noted the existence of westerlies near south equatorial west Pacific during January and February. Does this zone of westerlies move northward with time and cover the Indian land mass during the northern summer? To verify this, we present $< u >$ from 40°E to 120°E for the months of January, March, May, July, September and November in figure 4. The zone of westerlies is seen around 8°S in January, it weakens in March and moves up to 5°S. In May, it moves further north up to the equator and merges with the westerlies coming from the north. In July, the combined westerlies intensify and in September, the zone of westerlies starts retreating and by November it almost moves south of the equator. In order to examine the meridional oscillation of this zone of westerlies in detail, a $y - t$ diagram of $< u >$ averaged over longitudes from 40°E to 120°E is presented in figure 5. A smooth meridional oscillation of westerlies is clearly seen with one year periodicity. The $y - t$ diagram indicates the pattern that connects the south equatorial westerlies of northern winter with the westerlies over the Indian land mass during northern summer.

According to Krishnamurti (1979) the major center of the Walker circulation lies over Indonesia during northern winter and over north Bay of Bengal during northern summer. The study of Waliser *et al* (1993) on tropical deep convection indicates that the major center of the Walker circulation over Indonesia and north Bay of Bengal is associated with deep convection. The meridional march of the deep convection with the season is very nicely presented in Joseph (1998). The center of deep convection lies over Indonesia during December and moves in the northward direction with the season and in June it is over Bay of Bengal. This zone of deep convection is mainly responsible for the existence of the lower tropospheric westerlies to its west. Stronger westerlies imply intense convective zone and the rainfall activity. Paul *et al* (1990) has also pointed out that strong monsoon westerlies are associated with active spells of rainfall. Thus, the strength of westerlies plays a dominant role in the rainfall activity.
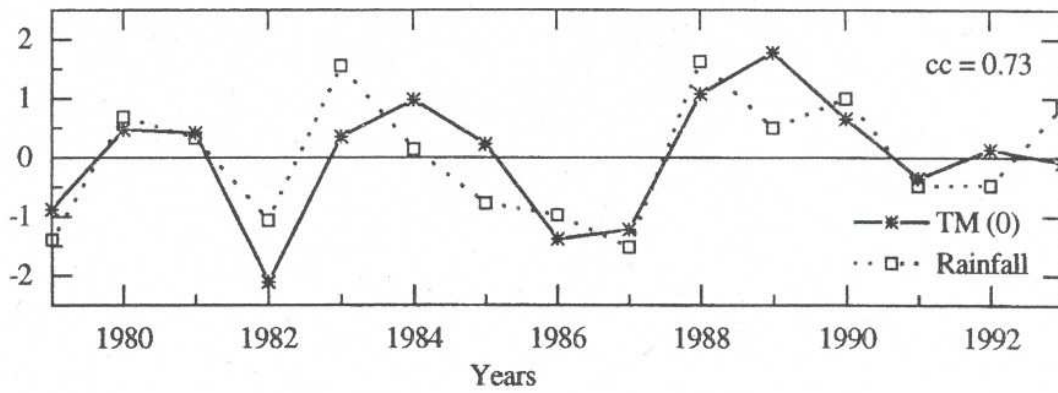
Figure 2. Momentum transport (m^2s^{-2}) of wave zero for the month of March at 850 hPa over latitudinal belt from 25°S to 5°N at 850 hPa and all-India monsoon rainfall (June to September).
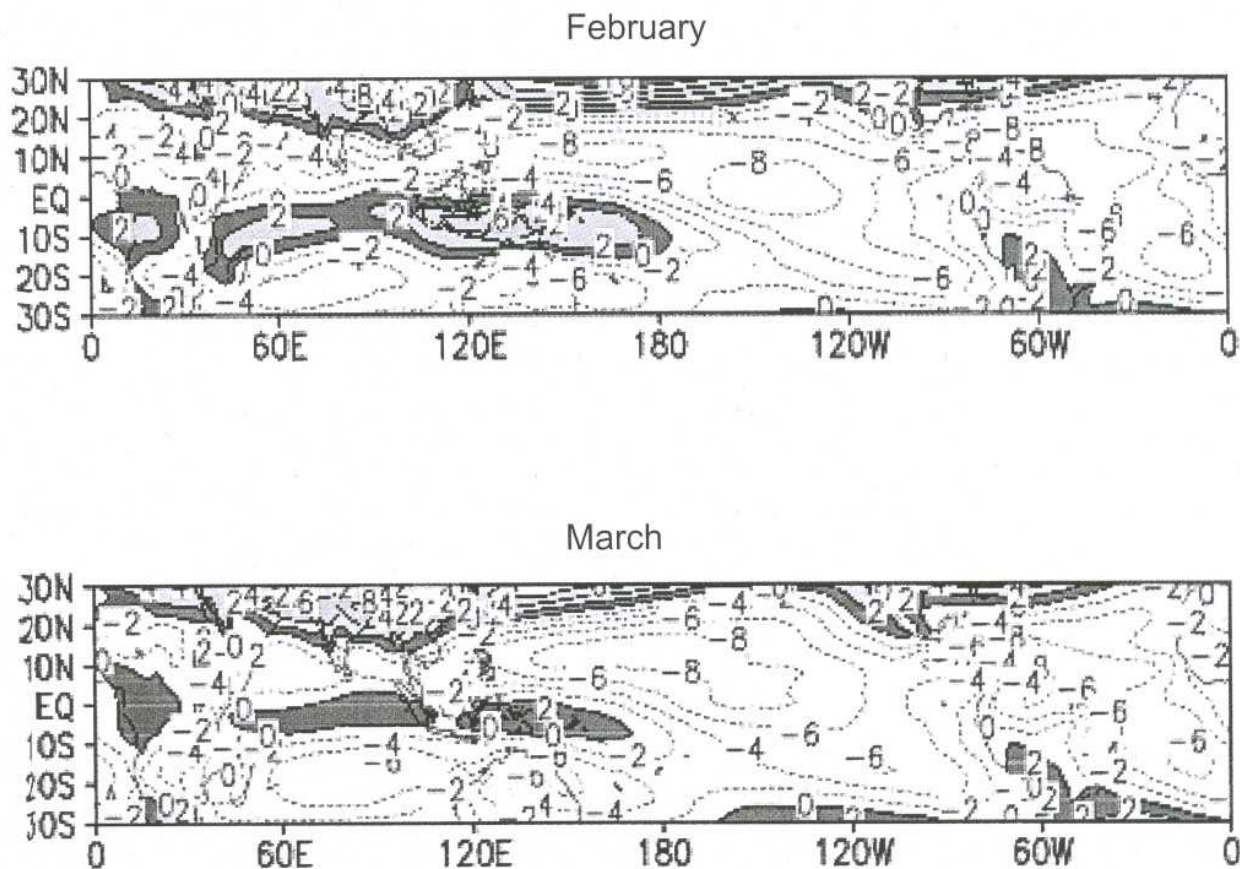
February

March

Figure 3. u mean (1979–1993) at 850 hPa for the months of February and March.

At this stage it would be interesting to examine the features of the zone of westerlies during contrasting monsoon seasons. We have selected 1987, 1988 and 1993 as the contrast in the westerlies is found to be well marked during these years. The year 1987 was a severe drought year associated with El Nino event, the year 1988 is one of the good monsoon seasons and the year 1993 was also a good monsoon season even though it is associated with El Nino event. Figure 6 gives zonal wind field of March for the above years. During 1987 the Indian Ocean is almost devoid of westerlies and experienced a severe drought condition with 697.3 mm of seasonal rainfall. During 1988, westerlies are well marked and extend from 40°E to 150°E. The maximum speed is more than 4 ms^{-1}

January

July

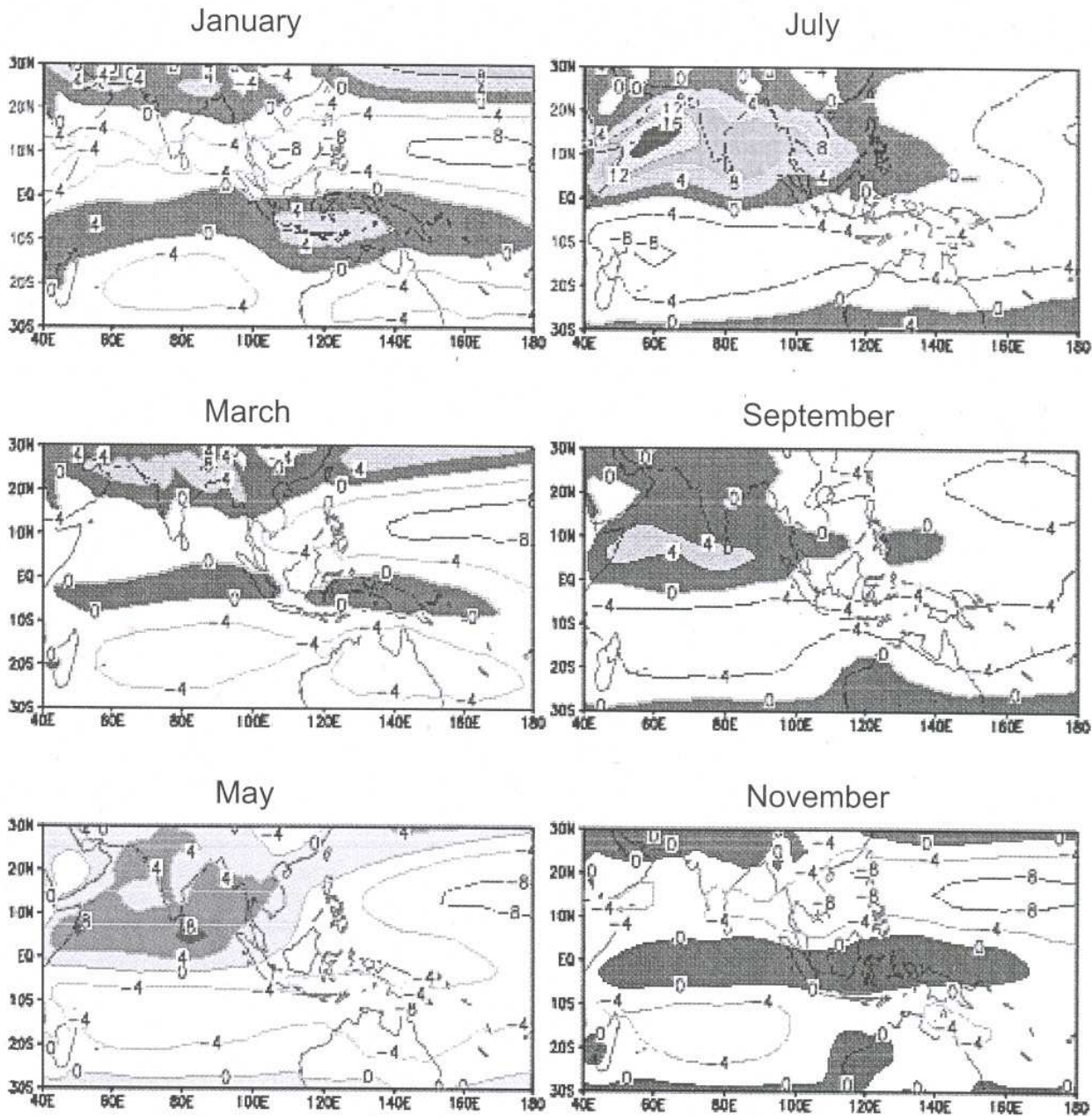
March

September

May

November

Figure 4. Meridional oscillation of the zone of westerlies in the Indian Ocean.

and the year is one of the very good monsoon years with a seasonal rainfall of 961.5 mm. The zone of westerlies during 1993 is not as intense as that of 1988, but it is well marked. Even though the year is associated with El Nino event, the monsoon rainfall was 896.7 mm. Figure 6 indicates that if the westerlies in the Indian Ocean are well marked in March, the subsequent monsoon will be good even if the year is associated with the El Nino event. Thus, the strength of the zone of westerlies in the Indian Ocean in March gives a signal about the performance of subsequent monsoon.

The present study suggests two predictors. TM(0) over LB can be used to predict the monsoon season quantitatively and the strength of the zone of westerlies in the Indian Ocean can predict the monsoon season qualitatively, two months in advance. It may be relevant to examine whether there exists an association between the two. We have seen in table 1 that average TM(0) over LB is positive during good monsoon years and negative during drought years. First, we will examine what causes TM(0) to be positive or negative. TM(0) is the product of $[u]$ and $[v]$ i.e., $[u][v]$, where $[\;]$ denotes the zonal average. We now exam-
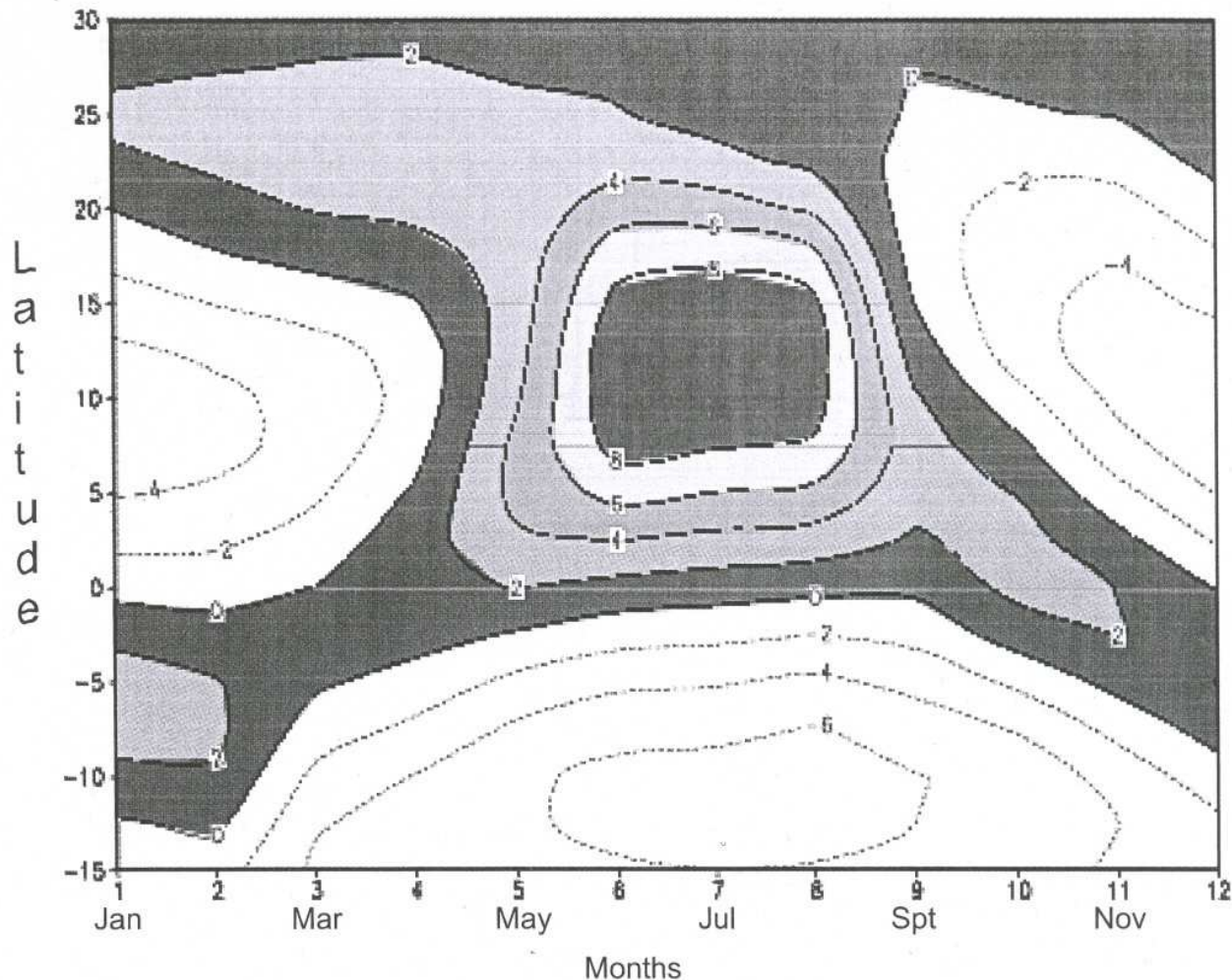
Figure 5.   Latitudinal and monthly variations of mean (1979–1993) u averaged over longitudes from 40°E to 120°E at 850 hPa.

ine the inter-annual variation of $[u]$, $[v]$ and $[u][v]$ over the belt LB (figure 7). The variation of $[u]$ and $[v]$ clearly shows that $[u]$ is one order larger (10 times) than $[v]$ and thus $[u]$ dominates the magnitude of TM(0). The zonal average of zonal wind $[u]$ is negative (easterlies) through out the belt LB, during all the years, even over the latitudes where the westerly zone exists. This indicates that contribution of westerly patch in the Indian Ocean to inter-annual variation of $[u]$ is insignificant. The zonal average of meridional component of wind $[v]$ is negative(southward) from 5°N to 5°S (EB) and positive (northward) from 5°S to 25°S (SB), while TM(0) is positive (northward) over EB and negative (southward) over SB. The sign of $[v]$ over these belt actually results the TM(0) into positive or negative as $[u]$ is negative over both the belts. If positive magnitude of TM(0) over EB is larger (smaller) than the negative magnitude of TM(0) over SB, the effective transport of TM(0) is posi-

tive (negative). Figure 7 clearly shows that during drought years (1979, 1982, 1986, 1987) the negative magnitude of TM(0) over SB exceeds the positive magnitude of TM(0) over EB resulting into effective negative TM(0) over the entire belt (LB). During normal years the reverse happens.

As the easterlies prevail over the entire belt, positive TM(0) over LB also means southward transport of easterlies and negative TM(0) means northward transport of easterlies. Thus, during the normal years there is effective southward transport of easterlies from the entire belt and during drought years there is effective northward transport of easterlies. Murakami (1974) has also shown that southward flux of easterly momentum in the southern latitudes increases during strong monsoon conditions and diminishes during weak monsoon situations. The effective southward transport of easterlies will favour the westerly zone in the Indian Ocean in its northward march by removing
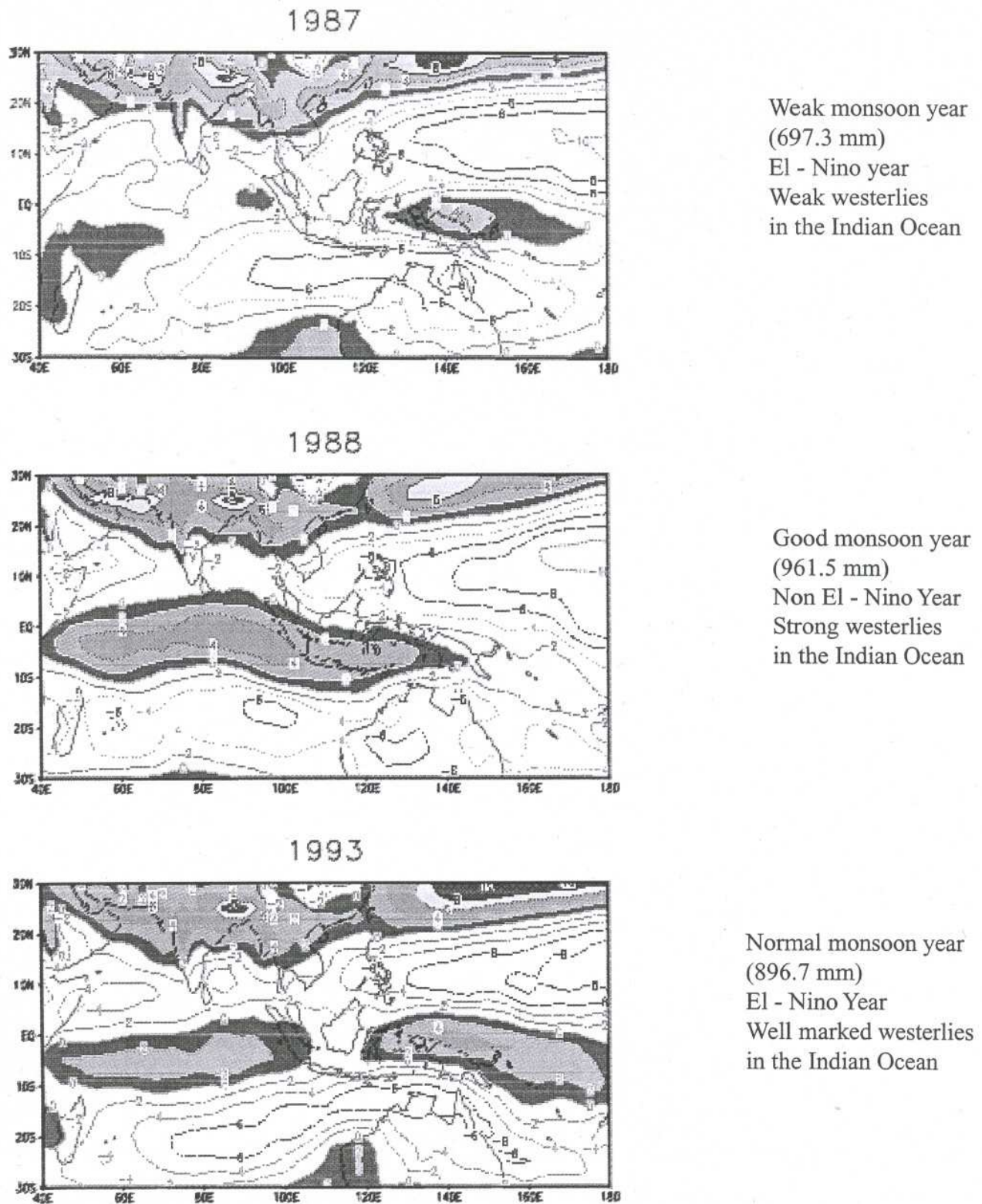
1987

Weak monsoon year
(697.3 mm)
El - Nino year
Weak westerlies
in the Indian Ocean

1988

Good monsoon year
(961.5 mm)
Non El - Nino Year
Strong westerlies
in the Indian Ocean

1993

Normal monsoon year
(896.7 mm)
El - Nino Year
Well marked westerlies
in the Indian Ocean

Figure 6.   *u*-field at 850 hPa for the month of March, for the years 1987, 1988 and 1993.

or weakening the easterlies from its way and effective northward transport of easterlies will create a hindrance in the northward march of westerly zone in the Indian Ocean by weakening or displacing the westerlies. The easterlies surrounding the zone of westerlies in the Indian Ocean are intense during drought year 1987 as compared to the easterlies during normal years 1988 and 1993 (figure 6). As
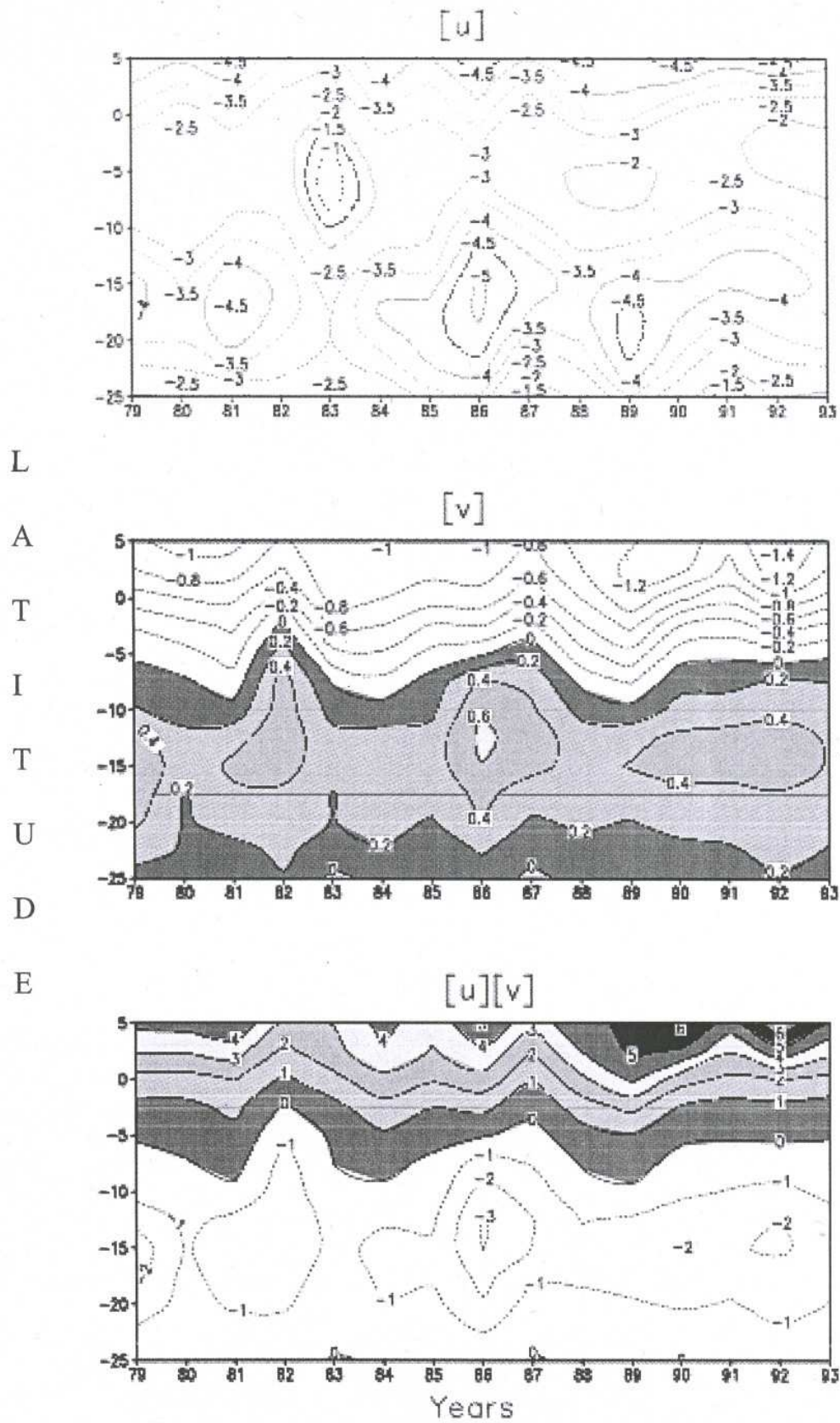
Figure 7.   Inter-annual variations of [u], [v] and [u][v].

discussed earlier, the westerly zone is associated with the center of deep convection. Stronger westerlies imply intense convective zone and rainfall activity. Weakening of westerly zone weakens the convection and rainfall activity. The displacement of westerly zone means displacement of the convective zone or rainfall zone. Thus, northward (southward) transport of TM(0) over LB strengthens (weakens) the westerly zone and also favours its northward march.

One of the components of TM(0) is $[v]$, which also represents the strength of the Hadley circulation. In the present study $[v]$ is the branch of the lower tropospheric Hadley circulation. A latitude where $[v]$ changes its sign represents either convergence or divergence. In the belt between 25°S and 5°N, $[v]$ changes its sign around 5°S. (figure 7). North of 5°S, the winds are southward and south of 5°S, the winds are northward, therefore 5°S represents the latitude of convergence or position of ITCZ for the month of March. In the present study, it is seen that the sign of TM(0) is controlled by $[v]$ and the strength of $[v]$ influences the convergence or ITCZ. Thus, $[v]$ is a common factor influencing ITCZ and TM(0). Similarly the Walker circulation influences $[u]$, which is one of the components of TM(0). Therefore, TM(0) is also influenced by the Walker circulation. Koteswaram (1958) has shown that Hadley circulation and Walker circulation are intense (weak) during normal (drought) monsoon seasons.

4. Concluding remarks

The study suggests two predictors, **(i)** Momentum transport of wave 0 (TM(0)) over 25°S to 5°N (LB) during March can provide a quantitative prediction of monsoon season and **(ii)** the strength of westerly zone of March in the Indian Ocean gives a qualitative prediction of monsoon, two months in advance. TM(0) influences the westerly zone through its effective northward/southward transport of easterlies over LB. TM(0), Hadley circulation, Walker circulation and ITCZ are interrelated. Zonal average of meridional wind $[v]$ is a common factor between the intensity of ITCZ and direction of TM(0). The other major findings of the study are: **(a)** The northward (southward) transport of momentum of wave zero in March over the latitudinal belt from 25°S to 5°N leads to a normal (drought) season over India, even if the year is associated with El Nino event and **(b)** If the westerlies in the Indian Ocean are well marked in March, the subsequent monsoon will be good even if the year is associated with the El Nino event.

Further work is required to ascertain whether or not the correlations we have seen here hold for a longer time-series. This is important because the IMR exhibits considerable inter-annual variability. In case the correlation is robust enough, it would be necessary to determine the dynamics behind the relationship. As the time-scale involved in the prediction covers almost seven months (approximately March to September) processes with long time-scales, such as atmosphere-ocean coupling might be important.

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