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Energetics of zonal waves during different phases of monsoon

S. M. BAWISKAR, M. D. CHIPADE

and

S. S. SINGH

Indian Institute of Tropical Meteorology,

Pashan, Pune-411008, India

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सार - इस शोध पत्र में 1994, 1995 और 1996 की अवधि में मानसून के आने, मानसून वर्षा होने की अवधि और मानसून की वापसी के दौरान निम्न क्षोभमंडलीय क्षेत्रीय तरंगों के ऊर्जा-विज्ञान का अध्ययन किया गया है। विश्लेषणों से यह पता चलता है कि क्षेत्र 1 (10° द. - 10° उ.) की तरंग 0, क्षेत्र 2 (10°उ. - 30° द.) की दीर्घ तरंगों (1 से 2 तक की तरंगें) तथा क्षेत्र 3 (30° उ. - 50°उ.) की लघु तरंगों (3 से 10 तक की तरंगें) का ऊर्जा - विज्ञान भारत में मानसून की सक्रियता को अन्तरा मौसमी पैमाने पर प्रभावित करता है।

क्षेत्रीय तरंगों के ऊर्जा-विज्ञान के साप्ताहिक विश्लेषण से यह पता चलता हे कि एल. 0 (12° द. - 3° उ.) अक्षांशीय क्षेत्र की तरंग 0, एल 1 (10° उ. - 15°उ.) क्षेत्र की तरंग 1 तथा एल 2 (33° उ. - 45°उ.) क्षेत्र की तरंग 2 का आवागमन संवेग अखिल भारतीय वर्षा के साथ साप्ताहिक स्तर पर संबंधित है। एल. 0 में तरंग 0 का बृहत्तर दक्षिणाभिमुखी आवागमन संवेग और एल 1 की तंरग 1 तथा एल. 2 की तरंग 2 के बृहत्तर उत्तराभिमुखी आवगमन सवेंग से भारत में मानसून की सक्रियता में वृद्धि होती है।

ABSTRACT. Energetics of lower tropospheric zonal waves during onset, established and withdrawal phases of monsoon have been studied for 1994, 1995 and 1996. The analysis show that energetics of wave 0 over R1 (10°S-10°N), long waves (waves 1-2) over R2 (10°N - 30°S) and short waves (waves 3-10) over R3 (30° N - 50° N) influence the monsoon activity over India on intra-seasonal scale.

The weekly analysis of the energetics of zonal waves indicates that the momentum transport of wave 0 over latitudinal belt L0 (12° S - 3° N), wave 1 over the belt L1(10° N - 15° N) and wave 2 over the belt L2 (33° N - 45° N) is related to all India rainfall on a weekly scale. Larger southward momentum transport of wave 0 over L0 and larger northward momentum transport of wave 1 over L1 and wave 2 over L2 enhance the monsoon activity over India.

Key words – Energetics, Fourier technique, Phases, Intra-seasonal.

1. Introduction

Indian monsoon interacts in quite a significant manner with other components of the global circulation. For example, the onset of monsoon over India is preceded by sudden intensification and northward shift of Mascarene high in south Indian ocean. Lower tropospheric monsoon flow over India gets considerable feed from the southern hemisphere across the equator. Sikka and Grey (1981) show that the subtropical Mascarene high undergoes short period intensity fluctuations due to the passage of tropical westerly waves of southern hemisphere. The intensification of Mascarene high strengthens the cross equatorial flow in term of the east African low level jet and corresponding monsoon current over the Arabian Sea. Nagra and Asnani (1978) relate 5-day periodicity in Indian monsoon activity with 5-day oscillation in African low level jet. Quasi-biweekly oscillation analysed by Krishnamurti and Bhalme (1976) relate monsoon rainfall over India to Monsoon Hadley cell extending to southern Indian ocean. There is also, a close relationship between monsoon activity over India and meteorological phenomena over the central and western Pacific. Ramamurthy (1972) has shown that when a severe break occurs over India, the lower tropospheric anticyclone axis shifts southward over western Pacific. Murakami (1976) has suggested that about five days after the onset of monsoon over central western India, the mid-Pacific upper level trough intensifies in response to the energy release over the monsoon region. Some of the studies also suggest that mid-latitude systems interact with Indian monsoon. Malurkar (1950) observes that after establishment of monsoon over India, southward extension of extra-tropical westerly troughs into northern India leads to a break in the Indian monsoon. Pisharoty and Desai (1956) conclude that western disturbances which are the remnants of middle latitude systems have significant effect on Indian weather during monsoon season. Chakravarthy and Basu (1957) conclude that greater the number of western disturbances lesser the number of eastern disturbances. Bedi *et al.* (1981) show that a strong monsoon is associated with strong westerlies and weak monsoon is associated with weak westerlies and westerly system of middle latitude are more active during a weak monsoon. All these studies clearly indicate that Indian monsoon is more than a local phenomena and interacts significantly with global circulation.

There are a number of studies which also indicate that the energetics of planetary waves influences the seasonal (June-September) rainfall over India. Murakami (1974) shows that the southward flux of easterly momentum into southern hemisphere increases during strong monsoon condition and diminishes during weak monsoon situation. Asnani and Awade (1978) observe that there is excessive transfer of momentum and deficient transfer of sensible heat from tropical region to mid-latitude region during good monsoon years and reverse happens during the years of weak monsoon. Krishnamurti and Kanamitsu (1981) have found that wavenumber 3 loses kinetic energy to zonal mean flow during good monsoon year where as it receives kinetic energy from zonal mean flow during drought monsoon year. Bawiskar *et al*. (1989) have found that at 20°N momentum transport of wavenumber 1 is four times larger during normal monsoon years as compared to that of drought monsoon years. Bawiskar and Singh (1992) have shown that during drought monsoon years the zonal mean flow is strong, small scales eddies are weak and there is a negative (positive) imbalance of kinetic energy in the region of easterlies (westerlies) due to wave to wave interaction. While during normal monsoon years the zonal mean flow is weak, the small scale eddies are strong and there is a positive (negative) imbalance of kinetic energy in the region of easterlies (westerlies) due to wave to wave interaction.

As the studies are based on the seasonal scale, the intra-seasonal variations are suppressed. Intra-seasonal variations of the energetics of the zonal waves during monsoon are not so far extensively studied. Monsoon season itself consists of three phases namely onset phase, established phase and withdrawal phase. In the present study we wish to look into the lower tropospheric energetics of zonal waves during different phases of monsoon to see if there exists any relationship between energetics of zonal waves and monsoon rainfall on intra-seasonal scale. The lower tropospheric energetics is considered, as the substantial fluctuations occur in the lower troposphere and to a lesser degree in the upper troposphere (Unninayar and Murakami,1978).

2. Data

Daily zonal (u) and meridional (v) wind data at 850 hPa for the period from 1 June to 30 September (122 days) for 1994, 1995 and 1996 are utilized for constructing the lower tropospheric energetics. The data are provided by National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi. The NCMRWF has a version of NCEP data assimilation system which provides better data set over Indian region. The data are at 1.5° × 1.5° lat./long. interval. The global area considered is between 12° S and 51° N.

Weekly actual rainfall data during the monsoon seasons of 1994, 1995 and 1996 are taken from the weekly weather reports of India Meteorological Department and all-India (India taken as one unit) weekly rainfall series are prepared.

3. Methodology

The wind data are subjected to Fourier analysis. The advantage of Fourier technique is that the observed field gets decomposed into independent components called zonal waves. These waves are nothing but the eddies in the zonal mean flow. For example, u is expressed as,

$$u(\lambda) = \frac{a_0}{2} + \sum_{m=1}^{N/2} a_m \cos\left(\frac{2\pi m\lambda}{N}\right) + b_m \sin\left(\frac{2\pi m\lambda}{N}\right)$$

The Fourier coefficients are computed as follows:

$$a_m = \frac{2}{N}\sum_{\lambda=1}^{N} u(\lambda)\cos\left(\frac{2\pi m\lambda}{N}\right)$$

TABLE 1

Periods for the different phases of monsoon

Years	Onset phase	Established phase	Withdrawal phase
1994	27 May - 30 June	1 July - 15 September	16 September - 17 October
1995	5 June - 13 July	14 July - 10 September	11 September- 15 October
1996	31 May - 30 June	1 July - 14 September	15 September- 15 October

$$b_m = \frac{2}{N}\sum_{\lambda=1}^{N} u(\lambda)\sin\left(\frac{2\pi m\lambda}{N}\right)$$

where m is the wave number, λ is longitude and N is number of grid points along a latitude circle.

The Fourier coefficients so computed are used to compute following parameters;

(*i*) Kinetic energy of zonal waves,

(*ii*) Momentum transport of zonal waves and

(*iii*) Wave to wave interactions.

The method for computing the above parameters is given in detail by Bawiskar *et al.* (1995).

4. Results and discussion

4.1. *Classification of waves*

In the present study we have considered first ten waves because eighty percent of variance is explained by first ten waves (Bawiskar *et al.*, 1992). The waves are further classified as follows:

(*i*) Zonal mean flow (wave 0),

(*ii*) Long waves (waves 1-2) and

(*iii*) Short waves (waves 3-10).

4.2. *Classification of regions*

The global area between 10° S and 50° N has been divided into three broad regions as follows. (The rational behind the following sub-division is given in detail by Bawiskar *et al.*, 2000).

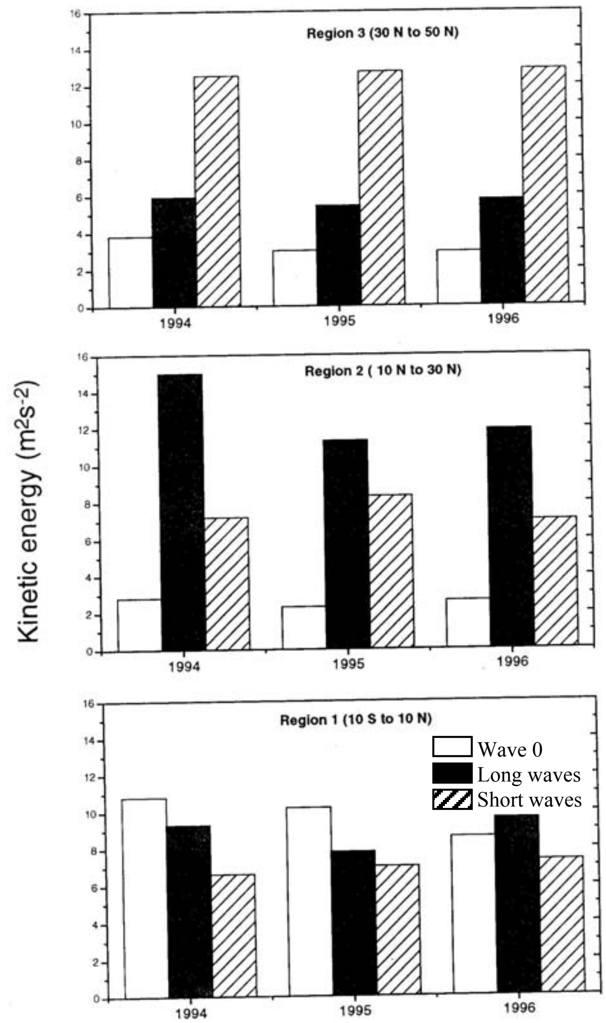

Fig. 1. Seasonal kinetic energy ($m^2 s^{-2}$) of wave 0, long waves (waves 1-2) and short waves (waves 3-10) over regions 1,2 and 3

(*i*) Region 1 (10° S - 10° N),

(*ii*) Region 2 (10° N - 30° N) and

(*iii*) Region 3 (30° N - 50° N)

Hereafter, these regions will be referred to as R1, R2 and R3 respectively.

4.3. *Different phases of monsoon*

Periods of the different phases of monsoons of 1994, 1995 and 1996 are taken from Mausam (1995, 1996, 1997) published by IMD and are given in Table 1.

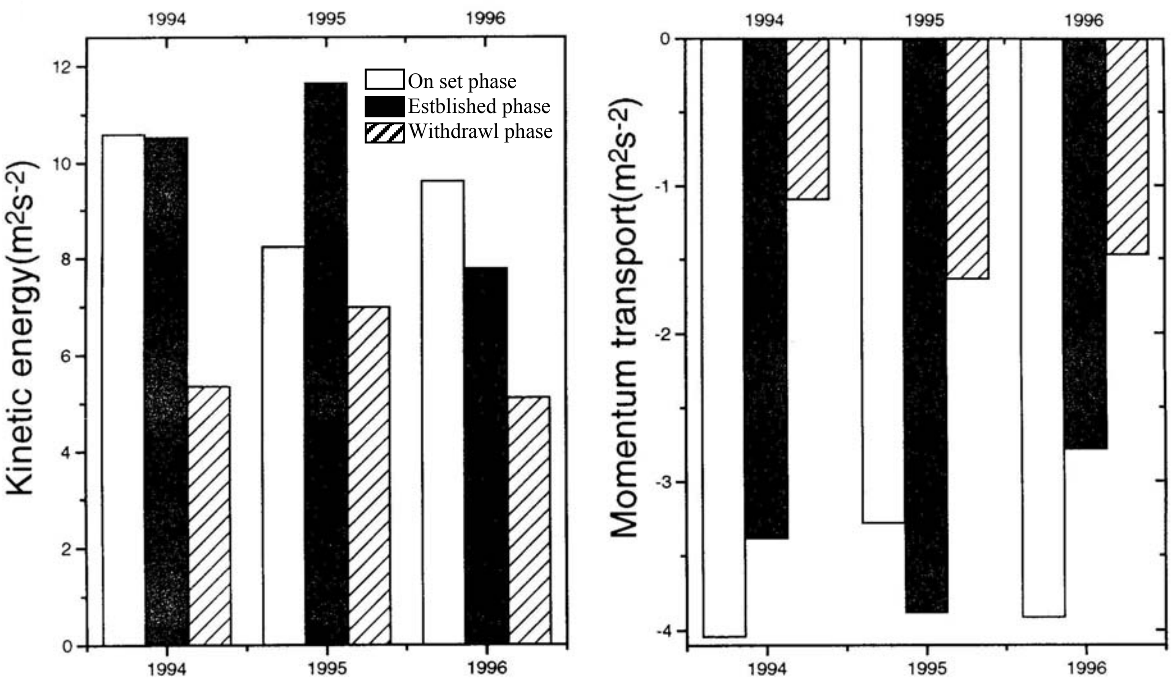

Fig. 2. Kinetic energy ($m^2 s^{-2}$) and momentum transport ($m^2 s^{-2}$) of wave 0 over R1 (10° S - 10° N)

We have computed mean energetics of zonal waves for Onset Phase (OP), Established Phase (EP) and Withdrawal Phase (WP).

4.4. *Energetics of zonal waves during different phases of monsoon*

We find that (Fig.1) wave 0, long waves and short waves dominate R1, R2 and R3 respectively on a seasonal scale (June-August) . Therefore we present the energetics of wave 0 over R1, long waves over R2 and short waves over R3 during OP, EP and WP.

4.4.1. *Wave 0 over R1*

Fig. 2 gives kinetic energy and momentum transport of wave 0 over R1. There is a sharp decrease in the momentum transport during WP. It is obvious, because stronger the zonal flow larger will be the kinetic energy and momentum transport and stronger will be the cross equatorial flow. Strong equatorial flow in the Indian ocean leads to stronger westerlies over the Arabian Sea and Indian land mass. Paul *et al*. (1990) have pointed out that strong monsoon westerlies are associated with active spells of rainfall. This indicates that energetics of wave 0 over R1 influence the Indian monsoon on intra-seasonal scale.

4.4.2. *Long waves over R2*

Fig. 3 gives energetics of long waves over R2. Kinetic energy and momentum transport of long waves is more during OP and EP and minimum during WP. Wave to wave interactions indicate that long waves receive kinetic energy from other waves during OP and EP, while during WP they are source of kinetic energy to other waves which indicates that as long as, the long waves over R2 receive kinetic energy from other waves the monsoon will be active and as they start losing kinetic energy to other waves the monsoon becomes weak or starts withdrawing. This shows that long waves over R2 influence the Indian monsoon on intra-seasonal scale.

4.4.3. *Short waves over R3*

Fig. 4 gives kinetic energy and wave to wave interactions of short waves over R3. The figure indicates that the kinetic energy is maximum during WP and minimum during EP. Wave to wave interaction indicates that the short waves become significantly active during WP. This implies that there is an inverse relationship between energetics of short waves over R3 and Indian monsoon on intra-seasonal scale. In support of this statement we would like to mention observations of some of the studies.

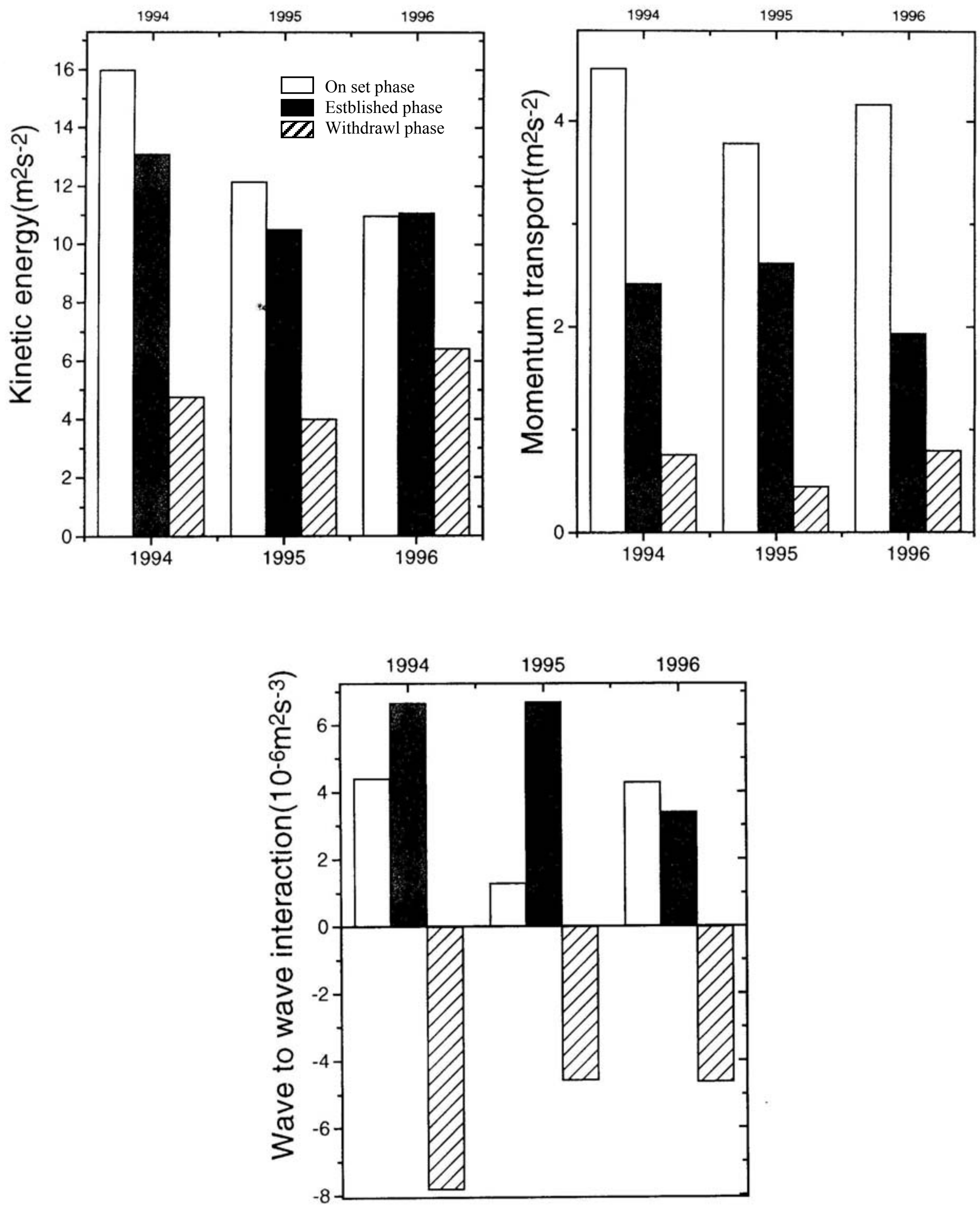

Fig. 3. Kinetic energy ($m^2 s^{-2}$) and momentum transport ($m^2 s^{-2}$) and wave to wave interactions (10^{-6} $m^2 s^{-3}$) of long waves over R2 (10° N - 30° N)

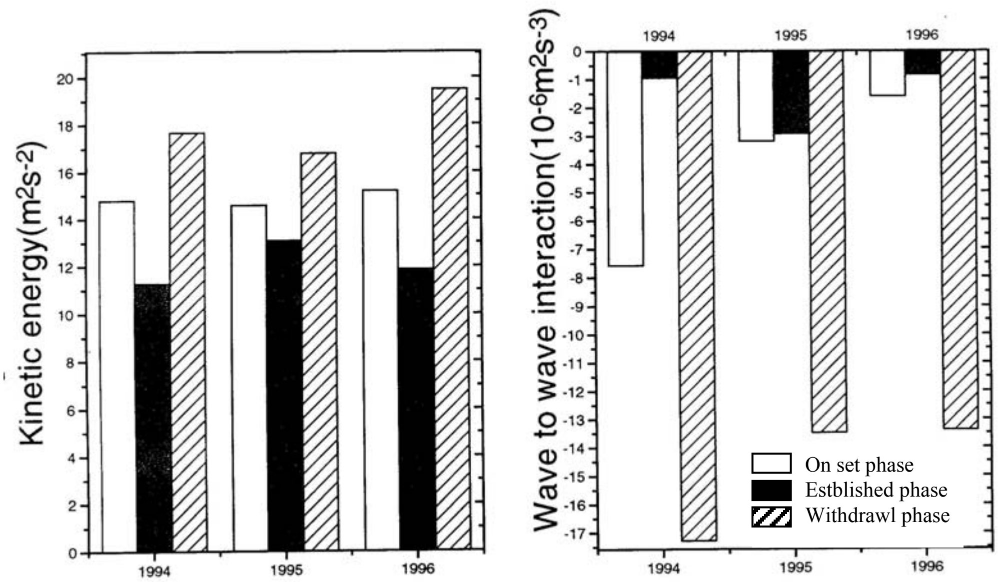

Fig. 4. Kinetic energy ($m^2 s^{-2}$) and wave to wave interaction (10^{-6} $m^2 s^{-3}$) of short waves (waves 3-10) over R3 (30°N - 50°N)

Chakravarthy and Basu (1957) show that greater the number of mid-latitude disturbance days the lesser the number of eastern disturbance days. Bedi *et al.* (1981) observe that systems in the westerlies (mid-latitude) are more active during weak monsoon. Pisharoty and Desai (1956) conclude that mid-latitude systems have significant effect during monsoon season.

4.5. *Weekly relation*

The results during different phases of monsoon clearly indicate that wave 0 over R1, long waves over R2 and short waves over R3 influence the Indian monsoon on intra-seasonal scale. On this basis, we have performed the correlation analysis between energetics of zonal waves and performance of monsoon. We have found that momentum transport of zonal waves show significant relationship with all India rainfall on weekly scale for all the three monsoon years under consideration. The other parameters do not have consistency. Therefore, we discuss the results of momentum transport of zonal waves only.

We have considered weekly all India rainfall series for 1 June to 30 September. A correlation analysis between weekly all India rainfall and weekly momentum transport of zonal waves is performed and it is observed that the correlations between momentum transport of waves 0,1 and 2 over some latitudinal belts and all India rainfall on weekly scale are significant. The latitudinal variations of CCs between waves 0,1and 2 and all India rainfall on weekly scale are presented in Fig. 5. The vertical dotted lines at

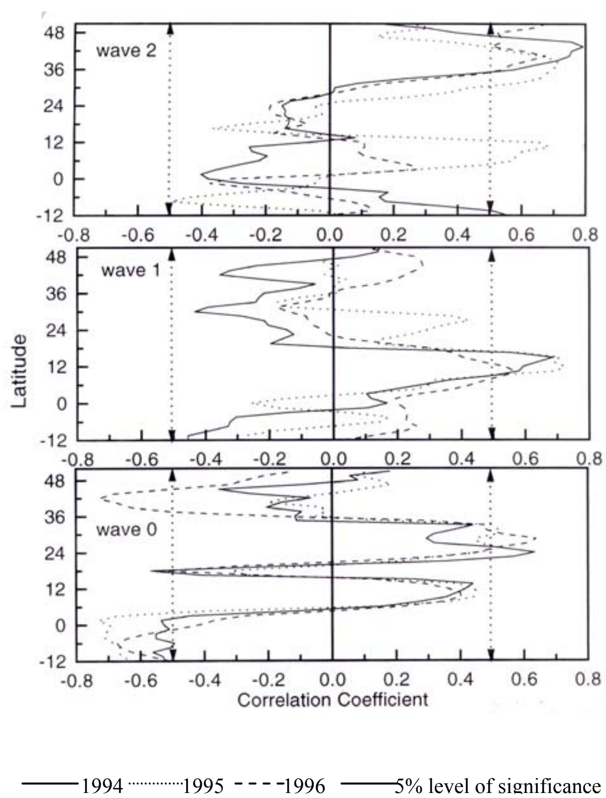

Fig. 5. Latitudinal variations of correlation coefficients of momentum transport ($m^2 s^{-2}$) of waves 0,1 and 2 with all India weekly rainfall

±0.5 represent the 5% level of significance. The CCs crossing these lines are highly significant. In case of wave 0, the significant CCs are seen over the latitudinal belt between

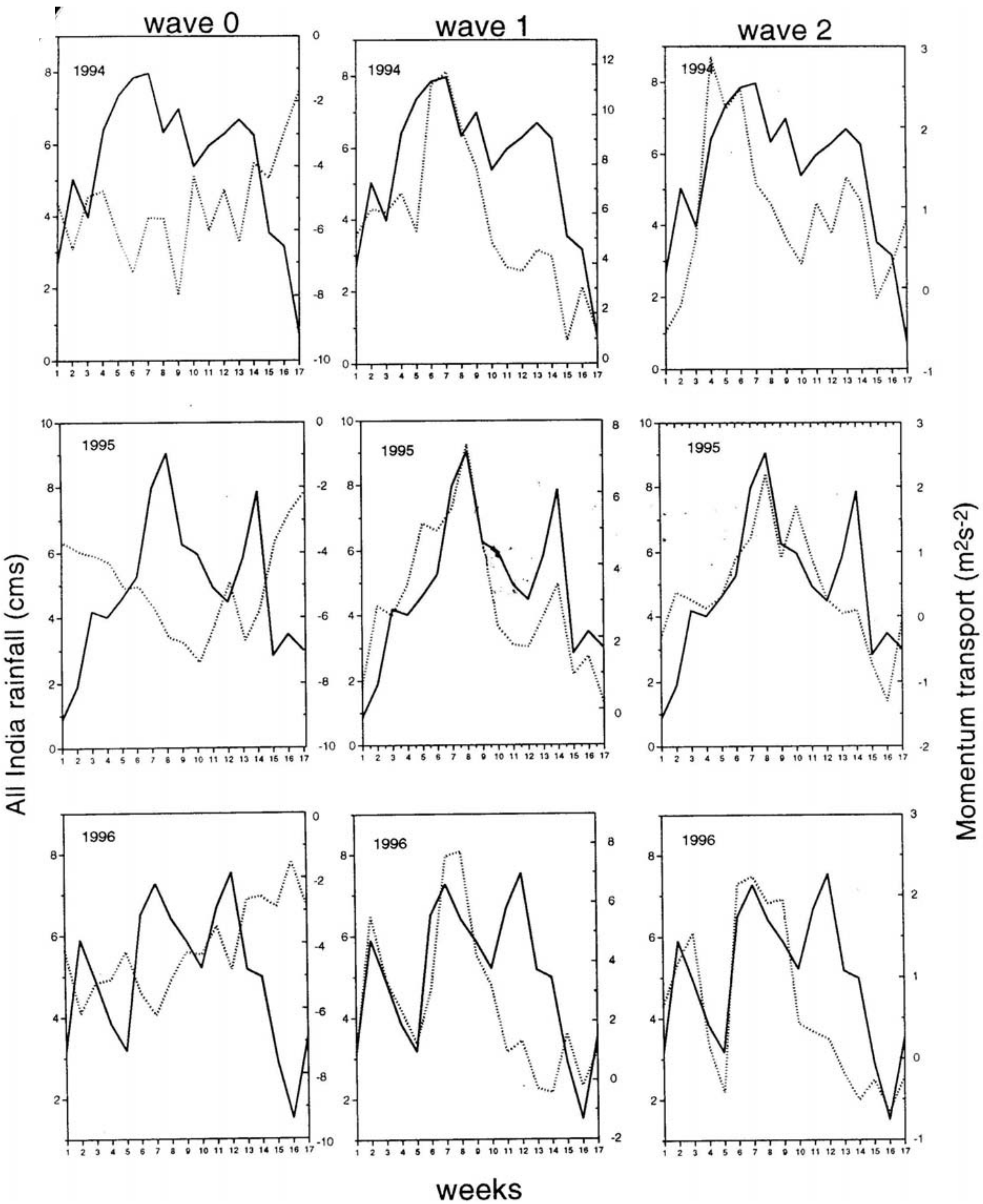

Fig. 6. Weekly variations of all India weekly rainfall (cm) and momentum transport ($m^2 s^{-2}$) of waves 0,1 and 2 for 1994, 1995 and 1996

12° S and 3° N. The negative significant CC of wave 0 implies inverse relationship. It means that when the northward transport of westerly momentum is large there is a weak monsoon and *vise-versa*. In other words it also means that larger southward of wave 0 over R1 is associated with active monsoon. Momentum of wave 1 has significant CCs over the latitudinal belt between 10° N and 15° N whereas wave 2 has significant CCs over the latitudinal belt between

33° N and 45° N. Hereafter, the global belts 12° S - 3°N, 10° N - 15° N and 33° N - 45° N will be referred to as L0, L1 and L2 respectively. The weekly variations of momentum transport of wave 0 over L0 and wave1 over L1 and wave 2 over L2 and weekly rainfall are presented in Fig. 6. The above results indicate that larger southward transport of momentum of wave 0 over L0 and larger northward transport of wave 1 over L1 and wave 2 over L2 enhance the monsoon activity over India.

5. Conclusions

The salient features of the study are summarized as follows:

Energetics of wave 0 over R1 (10° S - 10° N), long waves over R2 (10° N-30° S) and short waves over R3 (30° N - 50° N) influence the monsoon activity over India on intra-seasonal scale.

The weekly analysis of the energetics of zonal waves indicates that the momentum transport of wave 0 over L0 (12° S - 3° N), wave 1 over L1(10° N - 15° N) and wave 2 over L2 (33° N - 45° N) are related to all India rainfall on a weekly scale. Larger southward momentum transport of wave 0 over L1 and larger northward momentum transport of wave 1 over L1 and wave 2 over L2 enhance the monsoon activity over India.

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References

Asnani, G. C. and Awade, S. T., 1978, "Monitoring of semi permanent troughs and ridge in relation to monsoon", *Indian J. Met. Hydrol. & Geophys*., **29**, 1&2, 163-169.

Bawiskar, S. M., Awade, S. T. and Singh, S. S., 1989, "Harmonic analysis of summer wind at 200 hPa level during contrasting monsoon years over India", *Proc. Indian Acad. Sci. (Earth & Plan. Sci.)*, **98,** 365-373.

Bawiskar, S. M. and Singh, S. S., 1992, "Upper tropospheric energetics of standing eddies in wave number domain during contrasting monsoon activity over India", *Mausam*, **43**, 4, 403-410.

Bawiskar, S. M., Chipade, M. D., Paul, D. K. and Singh, S.S., 1995, "Upper and lower tropospheric energetics of standing and transient eddies in wave number domain during summer monsoon of 1991", *Proc. Indian Acad. Sci. (Earth & Plan. Sci.)*, **104**, 613-634.

Bawiskar, S. M., Chipade, M. D and Singh, S. S., 2000, "Energetics of the lower tropospheric eddies in wave number domain during northern summer monsoon", *Mausam*, **51, 2,** 119-126.

Bedi, H. S., Billa, H. S. and Mukarjee, N., 1981, "Interaction between northern middle latitude and summer monsoon circulation", Int. Conf. on early results of FGGE and large scale aspects of monsoon experiment GARP, Tallhasseee, Florida, 12-17 Jan 1981, p5-25 to 5-29.

Chakravarthy, K.C. and Basu, S.C., 1957, "The influence of western disturbance on the weather over northeast India in monsoon months", *Indian J. Met. & Geophy*. , **8**, 261-272.

Krishnamurti, T. N. and Bhalme, H. N., 1976, "Oscillations of monsoon system : Part I, observational aspect", *J. Atmos. Sci.*, **33**, 1937-1954.

Krishnamurti, T. N. and Kanamitsu, M., 1981, "Northern summer planetary scale monsoon during drought and normal rainfall months", In Monsoon dynamics (Eds.), Sir James Lighthill and R. P. Pearce (Cambridge : University Press), 19-48.

Malurkar, S. L., 1950, "Notes on analysis of weather of India and neighbourhood", *Memoirs of India Meteor. Deptt.*, **28**, 49, 139-215.

Murakami, T., 1974, "Steady and transient waves excited by diabatic heat sources during the summer monsoon season", *J. Atmos. Sci*., **31**, 340-357

Murakami, T., 1976, "Cloudiness of fluctuations during the summer monsoon", *J. Meteor. Soc. Japan,* **54**, 175-181.

Nagra, T. and Asnani, G. C., 1978, "Five day oscillation in East African low level jet", *Nature,* **272**, 708-709.

Paul, D. K., Mujumdar, V. R., Puranik, P. V., Ghanekar, S.P., Deshpande, V. R. and Sikka, D. R., 1990, "Fluctuation of regional scale atmospheric features in relation to monsoon activities", *Mausam,* **41**, 2, 309-314.

Pisharoty, P.R. and Desai, B.N., 1956, "Western disturbances and Indian weather", *Indian J. Met. & Geophys.*, **7**, 4, 333-338.

Ramamurthy, K., 1972, "Case study of heat wave during July 1966", *Indian J. Met. & Geophys.*, **23**, 2, 165-172.

Sikka, D. R. and Grey, W. M., 1981, "Cross hemispheric actions and the onset of summer monsoon over India", International Conf. on Sci.., Results of monsoon experiments, Bali, Indonesia, 26-30 October 1981, 3.74 to 3.78.

Unninayar, M.S. and Murakami, T., 1978, "Temporal variations in the northern hemispheric summer circulations", *Indian J. Met. Hydrol. & Geophys.*, **29**, 1 & 2, 170-186.