MAUSAM, 51, 2 (April 2000), 119-126

551.511.62 : 551.553.21

Energetics of the lower tropospheric eddies in wave number domain during northern summer monsoon

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(Received 17 November 1998, Modified 21 April 1999)

सार - इस शोध-पत्र में उत्तरी क्षेत्र की 1994, 1995 एवं 1996 की लगातार तीन ग्रीष्मकालीन मानसून ऋतुओं के क्षेत्रीय तरंगों से संबंधित निम्न क्षोभमंडलीय उर्जा-विज्ञान और ऊर्जा प्रक्रमों का विवरण प्रस्तुत किया गया है। इसके लिए फोरियर तकनीक प्रयुक्त की गई। इस अध्ययन के लिए प्रयुक्त किए गए डाटासेट से उष्णकटिबंधीय तथा बहिरूष्णकटिबंधीय क्षेत्रों की विशेषताओं पर समुचित विचार किया गया है। परिणामों से ऊर्जा प्रक्रमों की पद्धति में वर्ष दर वर्ष हुए उल्लेखनीय परिवर्तनों का पता नहीं चलता है। एक अक्षांशीय क्षेत्र के ऊर्जा प्रक्रमों की प्रकृति दूसरे अक्षांशीय क्षेत्र से विशेष रूप से भिन्न पाई गई है। क्षेत्र-1[10° दक्षिण -10° उत्तर] तथा क्षेत्र -2 [10° उत्तर - 30° उत्तर] में तरंग और कटिबंधीय माध्य प्रवाह अन्योन्यक्रिया तथा तरंग और तरंग अन्योन्यक्रियाओं में तरंग की प्रकृति लगभग विपरीत पाई गई है। *L*(*n*) अन्योन्यक्रियाओं से यह पता चलता है कि क्षेत्र - 2 की तरंगों के लिए क्षेत्र - 1 गतिज ऊर्जा के स्रोत के रूप में कार्य करता है। क्षेत्र - 1 की 1 और 2 स्थायी तरंगें विशेष रूप से क्षेत्र - 2 की तरंगों के लिए गतिज ऊर्जा का मुख्य स्रोत हैं। बहिरूष्णकटिबंधीय क्षेत्र अर्थात क्षेत्र - 3 [30° उत्तर - 50° उत्तर] अस्थायी तरंगों से प्रमुख रूप से प्रभावित रहता है, जबकि उष्णकटिबंधीय क्षेत्र अर्थात क्षेत्र -1 और क्षेत्र - 2 स्थायी तरंगों से प्रमुख रूप से प्रभावित रहते है। बहिरूष्णकटिबंधीय क्षेत्र में मध्यम एवं लघु तरंगों का उल्लेखनीय योगदान, जबकि उष्णकटिबंधीय क्षेत्र दीर्घ तरंगों से प्रमुख रूप से प्रभावित होते है। क्षेत्र - 3 की ऊर्जा प्रक्रम पद्धति क्षेत्र - 1 के ऊर्जा प्रक्रमों से कुछ मिलती जुलती है, क्योकि दोनों क्षेत्र प्रति चक्रवात पार्श्व अपरूप है।

ABSTRACT. Lower tropospheric energetics and energy processes of zonal waves for three consecutive northern summer monsoon seasons of 1994, 1995 and 1996 are presented. Fourier technique is used. The features of the tropical and extra-tropical regions are very well reflected by the data set used for this study. The results do not show marked year to year variations in the pattern of energy processes. The character of energy processes differs significantly from one latitudinal region to other. Wave to zonal mean flow interactions and wave to wave interactions are almost opposite in character over R1 (10° S –10° N) and R2 (10° N – 30° N). $L(n)$ interaction indicates that R1 acts as source of kinetic energy to the waves over R2. Particularly, standing waves 1 and 2 over R1 are the major source of kinetic energy to the waves over R2. Extra-tropical region R3 (30° N – 50° N) is dominated by transient waves while tropical regions R1 and R2 are dominated by standing waves. Medium and short waves have significant contributions over extra-tropical region whereas tropical regions are dominated by long waves. The pattern of energy processes over R3 is somewhat similar to the energy processes over R1. This is because both the regions have anti–cyclonic lateral shear.

Key words – Energetics, Lower troposphere, Wave number domain, Fourier technique.

1. Introduction

Zonal asymmetry between land and ocean in the tropics plays a dominant role in the dynamics of the tropical atmosphere. During northern summer (June – August), the lower tropospheric temperature, pressure, wind direction, humidity and circulation features over land and ocean show a marked contrast. Lands are warmer than the oceans causing lows over land and highs over ocean. Zonal wind is westerly over land and easterly over ocean while meridional wind is southerly over land and northerly over ocean. Lands are humid and oceans are

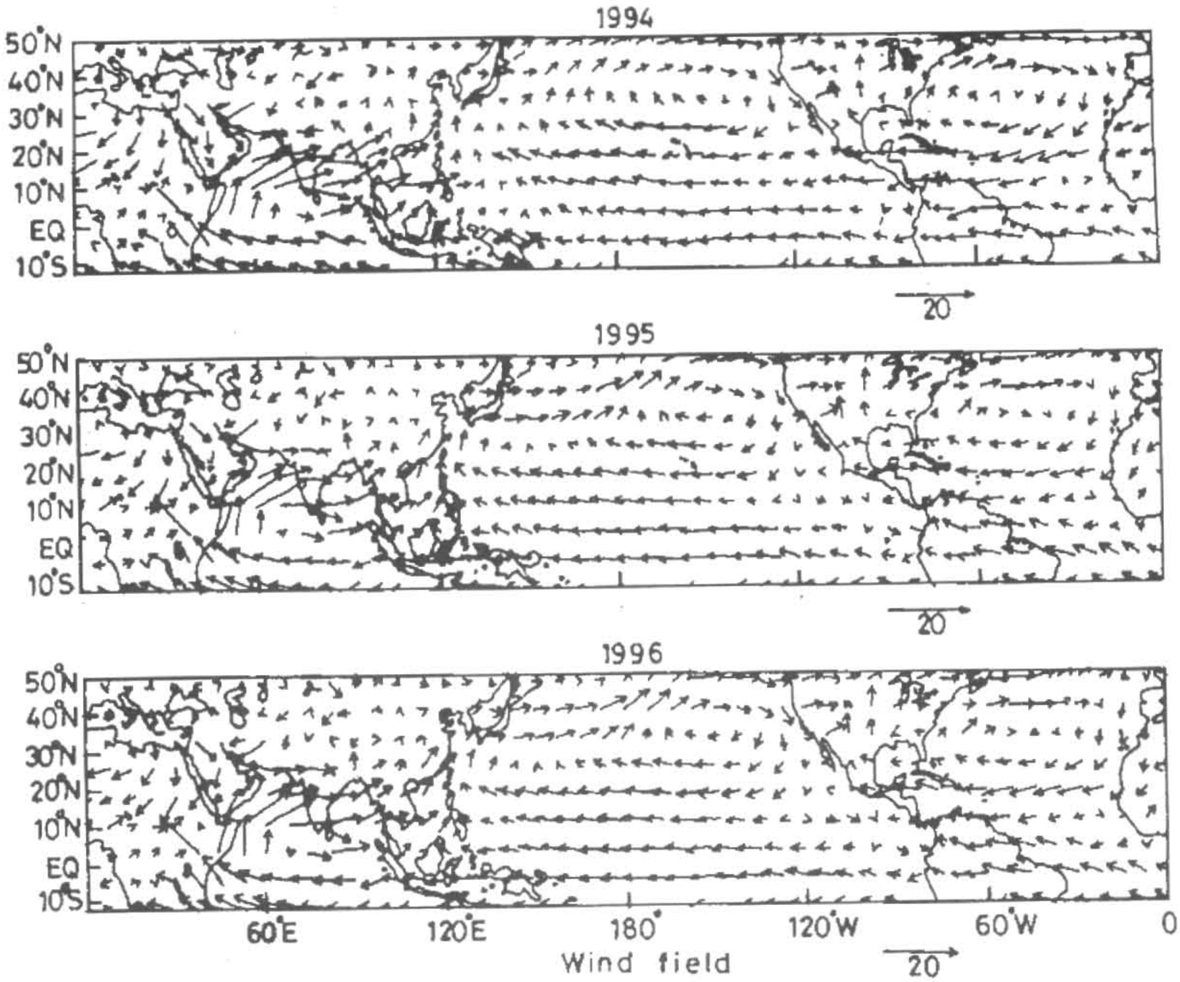

Fig. 1. Seasonal (June-August) wind field at 850 hPa

relatively dry. These contrasting features persist throughout northern summer and are mainly responsible for the generation of standing eddies. The low-level jet, heat low over Pakistan, oceanic anticyclones and cyclonic circulation over Indian sub-continent are the major standing eddies which are seen throughout the northern summer in the lower troposphere in the tropics. Performance of summer monsoon mainly depends upon the intensity of some of these standing eddies. Intensity of the eddies is directly related to the wind speed or the kinetic energy. One of the methods of studying the energetics of the eddies is through one dimensional Fourier analysis (Space-spectral analysis). The advantage of the Fourier technique is that the observed field gets decomposed into various independent harmonics called zonal waves which are nothing but the eddies in the zonal mean flow. Further, the first few components (harmonics) approximate the total field and thereby reduce the number of independent components. The other advantage of this technique is that with the help of Fourier coefficients we can compute kinetic energy of waves and exchange of kinetic energy among the waves and between the waves and zonal mean flow.

The energetics of the upper tropospheric zonal waves have been extensively studied by many workers (*e.g.* Saltzman, 1970; Unni-nayar and Murakami,1978; Krishnamurti and Kanamitsu, 1981; Murakami, 1981; Awade *et al.*, 1982,1984,1986; Bawiskar *et al.*, 1989, 1995 and Bawiskar and Singh, 1992). A very little work has been done relating to the energetics of the lower tropospheric zonal waves, possibly due to the orography as the lower tropospheric data around the mountains are tentative. However, the area coverage of such tentative data is very small (less than 10%) as compared to the data coverage of complete latitude circle, and that too for latitudes between 25° N and 35° N (around Himalayas) and such it may have marginal effect on the kinetic energy of the zonal waves. Recently, Krishnamurti *et al.* (1992) variance is described by first 6 to 7 zonal harmonics.

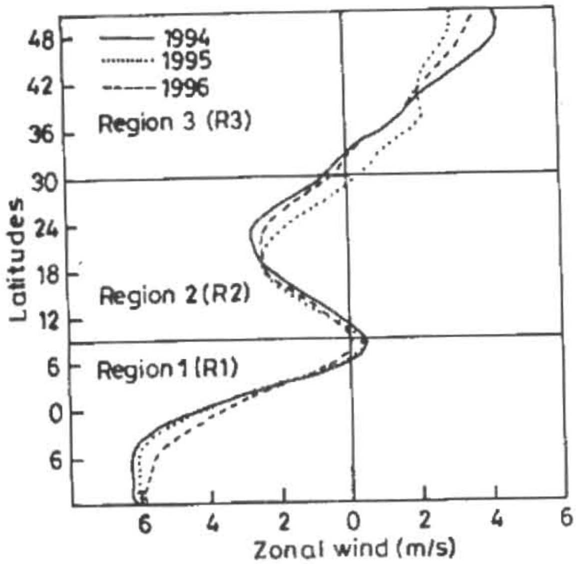

Fig. 2. Latitudinal variations of seasonal (June-August) and zonal average of zonal wind at 850 hPa

Bawiskar *et al.* (1998) showed that kinetic energy of wave number 1 has 30-40 day dominant mode by using 850 hPa wind data for the year 1991. In this paper we have presented the energetics of the lower tropospheric zonal waves using 850 hPa wind data.

2. Data

Daily u and v data at 850 hPa for the period from 1 June to 31 August (92 days) for three monsoon seasons of 1994, 1995 and 1996 are utilised for this study. The data were provided by National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi at 1.5° × 1.5° Lat./Long. interval for the global area between 10° S and 50° N.

3. Seasonal features of monsoon 1994, 1995 and 1996

3.1. *Seasonal wind field*

Fig. 1 gives seasonal (mean of 1 June to 31 August) wind field at 850 hPa for the years 1994, 1995 and 1996. The seasonal wind pattern is almost identical for all the three years. In the latitudinal belt between equator and 25°N the westerlies are prominently seen in the Arabian Sea and over the Indian landmass. These westerlies, which are the component of Somali jet, are the major agents transporting warm and moist air over Indian landmass. If we consider the complete global belt between equator to 25° N, the longitudinal coverage of westerlies is from 30°E to 120°E (which is 25% of the complete latitudinal belt) and rest of the belt is dominated by the easterlies. When average of complete latitude circle (zonal average) is considered the easterlies are only reflected. But for a small belt between 6° N and 10°N the average is marginally positive. Fig. 2 which indicates that the westerlies over this belt are so strong that even their longitudinal coverage is 25 %, the zonal average is reflected by westerlies only.

3.2. *Seasonal mean stream function*

Fig. 3 presents stream function charts at 850 hPa for northern summer monsoon seasons of 1994, 1995 and 1996. The stream function is computed from seasonal u and v components of wind.

A prominent cyclonic circulation is seen over NW India. A line separating easterlies to the north and westerlies to the south of this cyclonic circulation would represent the seasonal position of monsoon trough. The two oceanic anticyclones occupy nearly 75% of the total area considered for this study. Another anticyclonic circulation is seen in the Indian Ocean, which gives rise to generation of low level jet and cross equatorial flow. The major planetary circulations of northern summer monsoon are very well depicted with respect to their position, which indicates that the data used for this study adequately represents seasonal picture of the northern summer monsoon.

There is not much difference in the position of major planetary circulations from one year to other years. There are little changes in the shape and intensity of the eddies. We find that anticyclonic circulation in Indian Ocean is more intense during 1994 as compared to 1995 and 1996.

3.3. *Classification of regions*

The global area between 10° S and 50° N is divided into three broad latitudinal belts. The division is based on the latitudinal variation of zonal average of zonal wind (Fig. 2). Zonal component is considered because this component dominated the kinetic energy of zonal waves. These regions are as follows:

Region 1 (10° S - 10° N) : Zonal wind is easterly (Fig. 2). There is steady weakening of easterlies in the northward direction. This variation gives rise to anti-cyclonic lateral shear.

Region 2 (10° N - 30° N) : In this belt the easterlies intensify northward up to 18° N and then gradually weaken. The first half of this belt (10°N-18°N) gives rise to cyclonic lateral shear and the second half (18°N- 30°N) has anti-cyclonic lateral shear.

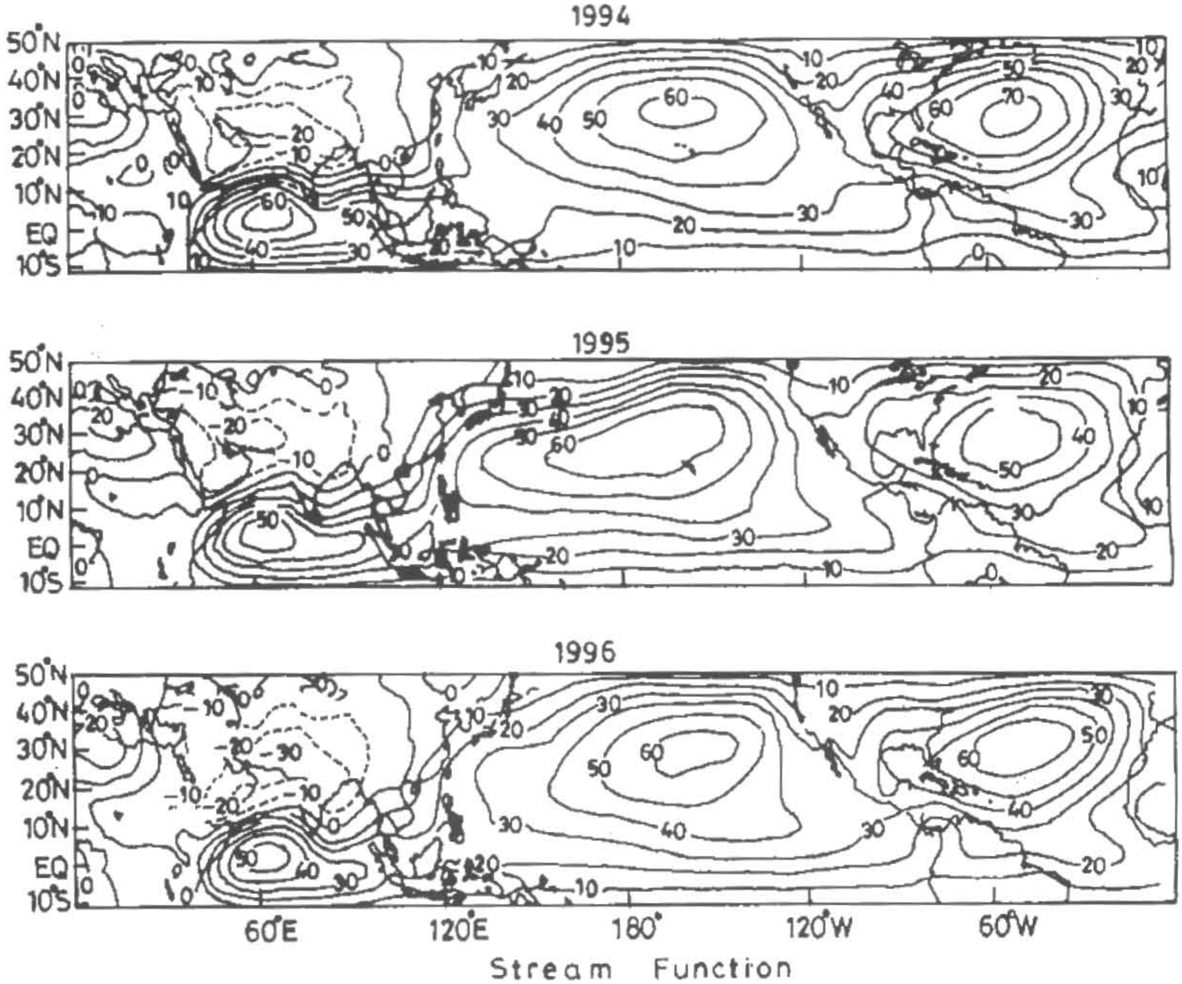

Fig. 3. Seasonal (June-August) stream function at 850 hPa (Unit: $10^6\ m^2s^{-1}$)

Region 3 (30°N - 50°N) : Zonal wind is westerly. The westerlies strengthen in the northward direction and give rise to anti-cyclonic lateral shear.

4. Methodology

Daily u and v data were decomposed into spectrum of zonal waves, for example u is expressed as

$$u(\lambda) = \frac{a_0}{2} + \sum_{n=1}^{\frac{N}{2}} a_n \text{ Cos} \left(\frac{2\pi\, n\lambda}{N} \right) + b_n \text{ Sin}\left(\frac{2\pi n\lambda}{N} \right)$$

where,

$$a_n = \frac{2}{N} \sum_{\lambda=1}^{N} u(\lambda) \text{Cos}\left(\frac{2\pi n\lambda}{N} \right)$$

$$b_n = \frac{2}{N} \sum_{\lambda=1}^{N} u(\lambda) \text{Sin}\left(\frac{2\pi n\lambda}{N} \right)$$

λ is longitude
N = 240 (grid points)
n is wave number

The Fourier coefficients a_n and b_n are used to compute the kinetic energy of wave number n, $K(n)$; the

TABLE 1

Kinetic energy of standing waves (SW) and transient waves (TW) at 850 hPa over R1, R2 and R3 (Unit : $m^2 s^{-2}$)

Regions	Waves	1994		1995		1996		Mean	
		SW	TW	SW	TW	SW	TW	SW	TW
R1 (10°S-10°N)	1	6.2	1.0	3.9	0.9	5.9	1.6	5.3	1.2
	2	1.3	0.8	2.2	0.8	1.3	0.8	1.6	0.8
	3-5	2.5	1.6	2.6	1.8	2.6	1.8	2.5	1.7
	6-10	1.0	1.5	0.9	1.7	1.2	1.7	1.0	1.6
	1-10	11.0	4.8	9.6	5.1	11.0	5.9	10.5	5.3
R2 (10°N-30°N)	1	9.3	1.1	5.1	1.1	6.0	1.6	6.8	1.3
	2	4.0	0.9	4.0	1.1	3.2	1.1	3.7	1.1
	3-5	1.6	2.2	1.3	2.2	1.2	2.2	1.4	2.2
	6-10	0.8	2.6	1.0	2.8	1.0	2.6	0.9	2.7
	1-10	15.6	6.8	11.3	7.2	11.4	7.6	12.8	7.2
R3 (30°N-50°N)	1	1.6	1.4	1.7	1.3	1.6	1.5	1.7	1.4
	2	1.0	1.9	0.8	1.6	0.9	1.7	0.9	1.7
	3-5	1.3	4.5	1.7	4.8	1.3	5.1	1.5	4.8
	6-10	0.8	5.9	0.8	6.4	0.7	5.7	0.8	6.0
	1-10	4.8	13.7	5.1	14.1	4.5	14.0	4.8	13.9

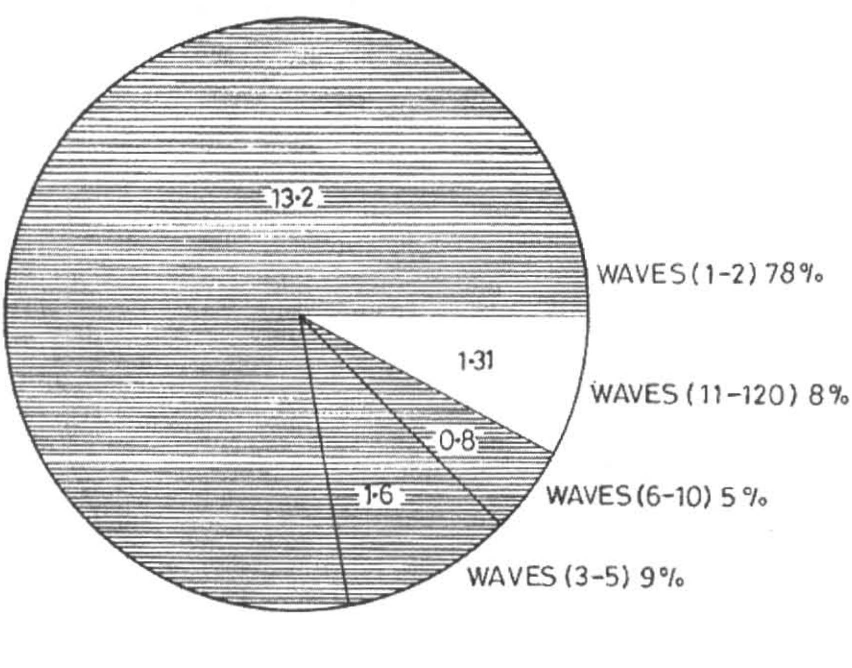

Fig . 4. Kinetic energy of long (waves 1 & 2), medium (waves 3-5), short (waves 6-10) and remaining (waves 11-120) waves

exchange of kinetic energy between wave number n and zonal mean flow, $M(n)$ and the exchange of kinetic energy between wave number n and all other waves, $L(n)$.

A detailed computational procedure of $K(n)$, $M(n)$ and $L(n)$ is given by Bawiskar and Singh (1992). As the total number of grid points along a latitude circle is 240,

TABLE 2

Wave to zonal mean flow interactions {$M(n)$}for standing waves (SW) and transient waves (TW) at 850 hPa over R1, R2 and R3 (Unit : 10^{-6} m^2 s^{-3})

Regions	Waves	1994		1995		1996		Mean	
		SW	TW	SW	TW	SW	TW	SW	TW
R1									
(10°S-10°N)	1	-11.0	-0.5	-7.0	0.1	-7.4	-0.8	-8.5	-0.4
	2	-0.3	0.2	-1.3	-0.2	-0.2	0.0	-0.6	0.0
	3-5	2.3	0.5	5.7	1.0	4.6	0.2	4.2	0.6
	6-10	-1.2	-0.2	-0.2	0.0	-0.7	-0.1	-0.7	-0.1
	1-10	-10.3	0.1	-2.7	0.8	-3.6	-0.9	-5.5	0.2
R2									
(10°N-20°N)	1	7.9	-0.6	3.4	-0.4	3.0	0.1	4.8	-0.3
	2	1.7	-1.1	0.1	-1.0	0.6	-1.4	0.8	-1.2
	3-5	0.7	0.6	0.5	1.0	0.4	1.1	0.6	0.9
	6-10	1.0	2.1	1.2	1.7	0.8	1.4	1.0	1.7
	1-10	11.3	1.1	5.2	1.2	4.8	1.1	7.1	1.1
R3									
(30°N-50°N)	1	-2.1	0.2	-1.7	-0.1	-1.8	0.1	-1.9	0.1
	2	-2.0	-1.1	-0.8	-1.0	-1.9	-0.5	-1.6	-0.9
	3-5	-0.6	-1.2	-0.4	-0.8	-0.7	-0.9	-0.5	-1.0
	6-10	-0.5	-3.7	-0.6	-3.3	-0.7	-4.2	-0.6	-3.7
	1-10	-5.2	-5.9	-3.5	-5.2	-5.0	-5.3	-4.6	-5.5

we can have maximum 120 waves. It is found that first 10 waves contribute more than 90 % of the total eddy kinetic energy (Fig. 4). Therefore, we have considered first 10 waves which are further classified in four categories; (*i*) long waves (wave numbers 1and 2), (*ii*) medium waves (wave numbers 3-5), (*iii*) short waves (wave numbers 6-10) and (*iv*) all waves (wave numbers 1-10)

5. Results

5.1. *Kinetic energy of waves, K (n)*

Table 1 gives kinetic energy of standing and transient waves for wave numbers 1,2,3-5 (medium waves), 6-10 (short waves) and 1-10 (total) for the years 1994, 1995 and 1996 and mean of these three years over R1, R2 and R3. Hereafter, standing waves and transient waves will be referred to as SW and TW respectively. Table 1 indicates following features:

(*i*) Wave-wise and region-wise distribution of kinetic energy for three years has similar pattern.

(*ii*) Over R1 and R2 the long waves are dominated by SW

(*iii*) The short waves over all the regions and medium waves over R2 and R3 are dominated by TW.

(*iv*) Wave numbers 1-10 (total) indicate that R1 and R2 are dominated by SW and R3 is dominated by TW. This is obvious because R1 and R2 are tropical regions while R3 is extra-tropical region and it is well known that extra-tropical region is dominated by transient waves and tropical region is dominated by standing waves. Thus, the features of tropical and extra-tropical regions are very well reflected.

5.2. *Wave to zonal mean flow interaction, M(n)*

Table 2 gives results of the wave to zonal flow interactions. Negative (positive) $M(n)$ means wave number n is source (sink) of the kinetic energy to the zonal mean flow. Table 2 indicates that:

(*i*) The pattern of $M(n)$ for the three years is almost similar.

(*ii*) Waves over R1 (except medium waves) and R3 supply kinetic energy to the zonal mean flow whereas waves over R2 (except few transient waves) receive kinetic energy from the zonal mean flow. In section 3.3 we have seen that R1 and R3 are having anticyclonic lateral shear and R2 is having both cyclonic and anticyclonic lateral shear. This shows that kinetic energy exchange between waves and

TABLE 3

Wave to wave interactions { $L(n)$} for standing waves (SW) and transient waves (TW) at 850 hPa over R1, R2 and R3 (Unit 10^{-6} m^2 s^{-3})

Regions	Waves	1994		1995		1996		Mean	
		SW	TW	SW	TW	SW	TW	SW	TW
R1 (10°S-10°N)	1	-12.4	-3.0	-8.9	-2.8	-12.3	-4.2	-11.2	-3.3
	2	-4.5	-0.3	-4.6	-2.4	-1.2	-0.9	-3.4	-1.2
	3-5	2.6	-0.1	4.0	0.1	5.5	-0.2	4.0	-0.1
	6-10	-3.5	0.2	-0.7	0.6	-2.6	0.3	-2.3	0.3
	1-10	-17.9	-3.3	-10.2	-4.5	-10.6	-5.0	-12.9	-4.3
R2 (10°N-20°N)	1	10.1	-6.3	3.2	-2.2	6.3	-3.6	6.5	-4.0
	2	6.8	-4.0	6.6	-2.8	5.7	-4.6	6.4	-3.8
	3-5	3.1	0.2	3.1	1.1	3.1	0.8	3.1	0.7
	6-10	1.1	2.4	2.4	-0.1	1.0	0.7	1.5	1.0
	1-10	21.0	-7.6	15.3	-4.0	16.1	-6.7	17.5	-6.1
R3 (30°N-50°N)	1	-0.8	-1.8	-0.4	-2.3	-0.5	-2.7	-0.6	-2.3
	2	2.5	-0.2	0.9	0.0	1.6	-0.9	1.7	-0.4
	3-5	-0.5	0.1	-1.3	1.8	-1.5	1.7	-1.1	1.2
	6-10	-1.5	-2.4	-0.4	-3.6	-0.7	-1.3	-0.9	-2.5
	1-10	-0.2	-4.3	-1.2	-4.1	-1.1	-3.3	-0.8	-3.9

zonal mean flow is mainly controlled by the type of lateral shear.

(*iii*) $M(n)$ interactions over R1 and R2 are dominated by SW and over R3, SW and TW have comparable contribution.

(*iv*) The direction of $M(n)$ interaction over R2 for standing and transient long waves is opposite.

5.3. *Wave to wave interaction*, $L(n)$

Results of the wave to wave interactions are presented in Table 3. Negative (positive) $L(n)$ means that wave number n is source (sink) of the kinetic energy to other waves *via* wave to wave interactions. Secondly, when the sum of $L(n)$ for $n = 1$ to 10 is negative (positive) over a particular region then that region is said to have surplus (deficit) kinetic energy. Waves over a region of surplus of kinetic energy supply the kinetic energy to the waves over a region of deficit kinetic energy. Table 3 further indicates that :

(*i*) Like $K(n)$ and $M(n)$, the $L(n)$ interaction have also similar pattern for three years.

(*ii*) $L(n)$ interaction is dominated by standing waves over R1 and R2 and by transient waves over R3.

(*iii*) R1 and R3 are the regions of surplus kinetic energy and R2 is the region of deficit kinetic energy.

6. Concluding remarks

Our earlier studies (Awade *et al.*, 1982 and 1984; Bawiskar *et al.*, 1989 and Bawiskar and Singh, 1992) show that the energetics of zonal waves exhibit contrasting character during normal and drought monsoon conditions over India whereas the results of this study do not show marked year to year variations in the pattern of energy processes during three northern summer monsoon seasons of 1994, 1995 and 1996. This is because all the three years considered for this study are normal monsoon years over India. The character of energy processes differ significantly from one latitudinal region to other. Wave to zonal mean flow interactions and wave to wave interactions are almost opposite in character over R1 (10°S-10°N) and R2 (10°N-30°N). $L(n)$ interaction indicates that waves over R1 act as source of kinetic energy to waves over R2. The extra-tropical region R3 (30°N-50°N) is dominated by transient waves while the tropical regions are dominated by standing waves. Medium and short waves have significant contributions over extra-tropical region whereas long waves dominate tropical region. The pattern of energy processes over R3 are somewhat similar to the energy processes over R1. This could be due to the fact that both the regions have anticyclonic lateral shears. The features of the tropical and extra-tropical regions are very well reflected in the study.

Acknowledgements

The authors are thankful to Dr G.B. Pant, Director, Indian Institute of Tropical Meteorology, Pune for his interest in the study. The grid point data are provided by NCMRWF, New Delhi.

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