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Upper and lower tropospheric energetics of standing and transient eddies in wave number domain during summer monsoon of 1991

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Abstract. Kinetic energy exchange equations (Saltzman 1957) in wave number domain are partitioned into standing, transient and standing-transient components following Murakami (1978, 1981). These components are computed for the 1991 summer monsoon using daily u and v grid point data at 2·5° latitude-longitude interval between the equator and 40°N at 200 hPa and 850 hPa levels for the period June through August. The data are obtained from NCMRWF, New Delhi.

The study shows that at 200 hPa wave number 1 over Region 3 (30°N to 40°N), wave number 2 over Region 2 (15°N to 30°N) and wave number 3 over Region 1 (equator to 15°N) dominate the spectrum of transport of momentum and wave to zonal mean flow interaction. Wave number 1 over Region 1 and Region 3 and wave number 2 over Region 2 are the major sources of kinetic energy to other waves via wave-to-wave interaction. At 850 hPa wave number 1 over Region 3 has maximum contribution in the spectrum of transport of momentum and kinetic energy and more than 90% of its contribution is from the standing component. This indicates that standing wave number 1 over Region 3 plays a very important role in the dynamics of monsoon circulation of the lower troposphere.

The study further shows that although the circulation patterns at 200 hPa and 850 hPa levels are opposite in character, a number of energy processes exhibit a similar character at these levels. For example, (i) transport of momentum by most of the waves is northward, (ii) small scale eddies intensify northward, (iii) eddies are sources of kinetic energy to zonal mean flow over Region 1 and (iv) standing eddies are sources of kinetic energy to transient eddies. Besides the above similarities some contrasting energy processes are also observed. Over Region 2 and Region 3 standing and transient eddies are sources of kinetic energy to zonal mean flow at 200 hPa, while at 850 hPa the direction of exchange of kinetic energy is opposite i.e. zonal mean flow is a source of kinetic energy to standing as well as transient eddies. $L(n)$ interaction indicates that at 200 hPa waves over R2 maintain waves over R1, while at 850 hPa waves over R1 maintain waves over R2.

It has been found that the north-south gradient of zonal mean of zonal wind is the deciding factor of wave to zonal mean flow interaction.

Keywords. Energetics; standing waves; transient waves

1. Introduction

The resolution of global wind field into a spectrum of spatial scales by one-dimensional Fourier analysis around a latitude circle has a unique advantage of decomposing the observed field into various independent components. These components are called scales or waves which are termed as eddies in the mean zonal flow. A wave whose wave length is equal to the circumference of a latitude circle is called wave number 1 and in general a wave whose wave length is equal to $(1/n)$th of the circumference of a latitude circle is called wave number n. Wave number zero represents zonal mean flow i.e.

average around a latitude circle. The field so decomposed is called wave number domain.

Graham (1955) showed that the first three harmonics of Fourier analysis approximate the hemispheric basic flow. He claimed that the Fourier technique simplifies the study by reducing the number of independent components. Saltzman (1957) derived spectral energy equations in wave number domain. Saltzman and Fleisher (1959, 1960) showed that wave numbers 5 to 10 are sources of kinetic energy to long and short waves. Keshavamurty and Awade (1974) compared the energetics of two contrasting monsoon years and found that smaller waves were more pronounced during the drought monsoon year as compared to the normal monsoon year. Unni-Nayar and Murakami (1978) examined changes in the kinetic energy of various tropical belts and pointed out that the upper tropospheric circulation displayed different characteristics in circulation during break and normal monsoon conditions over India. Krishnamurti and Kanamitsu (1981) examined the upper tropospheric large scale circulation features at 200 hPa for two contrasting monsoon years viz. 1967 and 1972. Murakami (1981) presented the energetics of standing and transient waves at 200 hPa. Studies of Awade *et al* (1982, 1984, 1986), Bawiskar *et al* (1989), Bawiskar (1990) and Bawiskar and Singh (1992) were restricted to the energetics of stationary waves.

In this paper we have presented the energetics of standing as well as transient waves at 200 and 850 hPa. Most of the studies mentioned above are related to energetics of the upper troposphere. The lower troposphere plays an equally important role in the energetics of monsoon, as such, we have considered 850 hPa level also. This will enable us to single out a particular wave dominating the circulation features of the lower troposphere.

2. Data

Daily u and v data at 200 hPa and 850 hPa levels for the period from 1st June to 31st August 1991 were utilized for this study. The data were provided by the National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi. Although the global grid point data are available at NMC, ECMWF, JMA and other advanced weather forecasting centres, the NCMRWF perhaps provides a better data set for tropical regions in general and over the Indian sub-continent in particular. Moreover, the NCMRWF has also a very sophisticated objective analysis and data assimilation system. These data contain objectively-analysed grided field cast on a $2{\cdot}5^\circ \times 2{\cdot}5^\circ$ latitude-longitude grid. We have considered the global area between the equator and 40°N.

The 1991 monsoon has been selected because it is one of the normal monsoons of recent years. During 1991, nearly 75% of the Indian land mass received excess or normal rainfall. The broad circulation features of monsoon 1991 at 200 hPa and 850 hPa are as follows:

2.1 *Circulation features at 200 hPa*

Figure 1(a) gives the mean stream function (Ψ) field at 200 hPa. The Ψ values are computed at each grid point using seasonal mean winds. The mean field is dominated

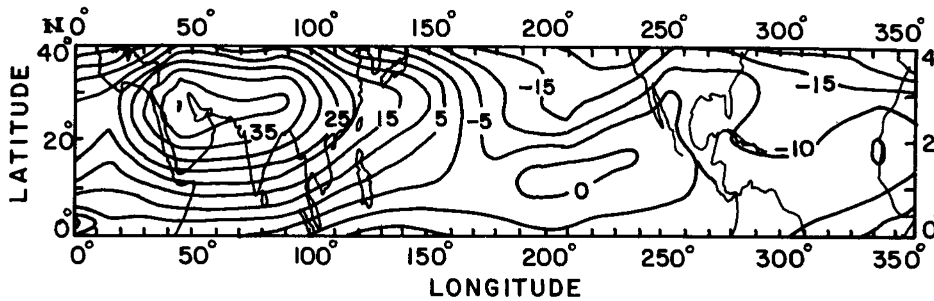

Figure 1(a). Summer mean (June – August) stream function field for 1991 at 200 hPa. Contour interval: $10^6 \, m^2 s^{-1}$.

by seasonal anticyclone (also called Tibetan anticyclone) and mid-Pacific and mid-Atlantic troughs. The centre of the Tibetan anticyclone as seen in figure 1(a) is slightly south-west of the one that was observed by Murakami (1981). Krishnamurti and Kanamitsu (1981) have observed the westward shift of the Tibetan anticyclone during a normal monsoon year.

2.2 *Circulation features at 850 hPa*

Figure 1(b) gives the mean stream function field at 850 hPa. The field is dominated by seasonal cyclonic circulation over Pakistan (which is the extension of surface seasonal heat low) and anticyclonic circulation in mid-Pacific and mid-Atlantic oceans. The circulation features of 200 hPa and 850 hPa are almost opposite in character. The seasonal features are very well depicted by the data set used.

3. Methodology

3.1 *Fourier representation*

Daily u and v data were decomposed into the spectrum of zonal waves. For example

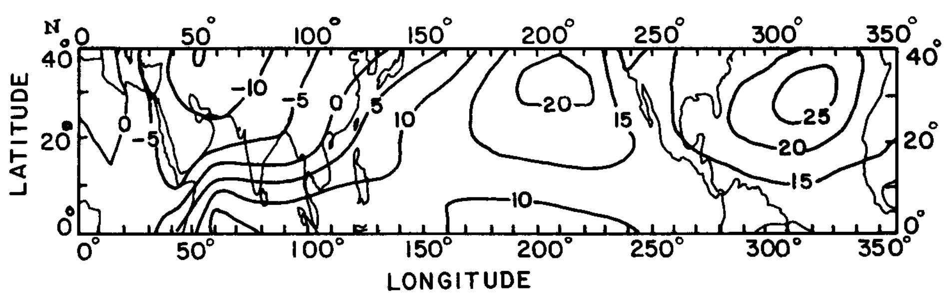

Figure 1(b). Summer mean (June – August) stream function field for 1991 at 850 hPa. Contour interval: $10^6 \, m^2 s^{-1}$.

u was expressed as

$$u(\lambda) = \sum_{n=-\infty}^{\infty} U(n) e^{in\lambda} \tag{3.1}$$

where,

$$U(n) = \frac{1}{2\pi} \int_0^{2\pi} u(\lambda) e^{-in\lambda} \mathrm{d}\lambda. \tag{3.2}$$

The quantity $U(n)$ is the spectral representation of $u(\lambda)$ in the domain of wave number.

Using the same symbol as Saltzman (1970), the energy equation for eddy kinetic energy can be written as

$$\frac{\partial K(n)}{\partial t} = M(n) + L(n) + C(n) - D(n) \tag{3.3}$$

where,

$K(n)$ = Total kinetic energy in eddies of wave number n.
$M(n)$ = Rate of transfer of kinetic energy between zonally averaged flow and eddies of wave number n.
$L(n)$ = Measures the flow of kinetic energy to eddies of wave number n from all other eddies.
$C(n)$ = Represents the conversion of eddy available potential energy to eddy kinetic energy for wave number n.
$D(n)$ = Dissipation term for wave number n.

Scale consideration indicates that the term $[uw]$ is much smaller than the term $[uv]$. Therefore, the terms containing w in $M(n)$ and $L(n)$ are not computed. We have not computed $C(n)$. As $D(n)$ is not based on direct measurement, it is also not computed.

We define the following notations for writing the equations for $M(n)$ and $L(n)$ in a compact form.

- (■) $u\beta_{uv}(n,m) = U(m)(U(-n)\,V(n-m) + U(n)\,V(-n-m))$.
- (■) $\gamma_{uv}(n) = (U(n)\,V(-n) + U(-n)\,V(n))$.
- (■) $|U(n)|^2 = U(n)U(-n)$.
- (■) $\alpha_{uv}(n) = U(-n)\,V(n)$.
- (■) $(u)_\phi = \dfrac{1}{a}\dfrac{\partial u}{\partial \phi}$.
- (■) $\sigma = \displaystyle\sum_{m=-\infty, m\neq 0}^{\infty} \frac{im}{a\cos\phi}$.

In the above notations the subscripts u and v are interchanging with one another resulting in corresponding changes in the spectral function.

While writing the equations, (n) or (n,m) on LHS of the above notations are dropped for convenience.

Using the above notations, we write

$$J(n) = \gamma_{uv}. \tag{3.4}$$

$$K(n) = |U(n)|^2 + |V(n)|^2. \tag{3.5}$$

$$M(n) = -\left(\gamma_{uv}\cos\phi\left(\frac{[u]}{\cos\phi}\right)_\phi + 2\alpha_{vv}([v])_\phi - 2\alpha_{uu}[v]\frac{\tan\phi}{a}\right). \quad (3.6)$$

$$L(n) = -\left(\sigma(u\beta_{uu} + v\beta_{vu}) + (u)_\phi\beta_{uv} + (v)_\phi\beta_{vv} + \frac{\tan\phi}{a}(u\beta_{vu} - v\beta_{uu})\right). \quad (3.7)$$

where $J(n)$ is the transport of momentum by wave n.

Partitioning of equations 3.4 to 3.7 into transient, standing and transient-standing components is given in Appendix I.

4. Result and discussion

In the present study we have decomposed the observed field into zonal waves. Theoretically we can have $N/2$ waves (where N is the number of grid points along a latitude circle). Generally the first few harmonics (waves) approximate the observed field. Therefore, we have considered the first ten waves only. Each wave, irrespective of its number, takes into account the effect of every grid point data along a latitude circle. When the data along a complete latitude circle are taken into account, it is the zonal wind that dominates over the meridional wind. So we have considered latitudinal variation of time averaged (June – August, 1991) zonal wind (see figure 2) for

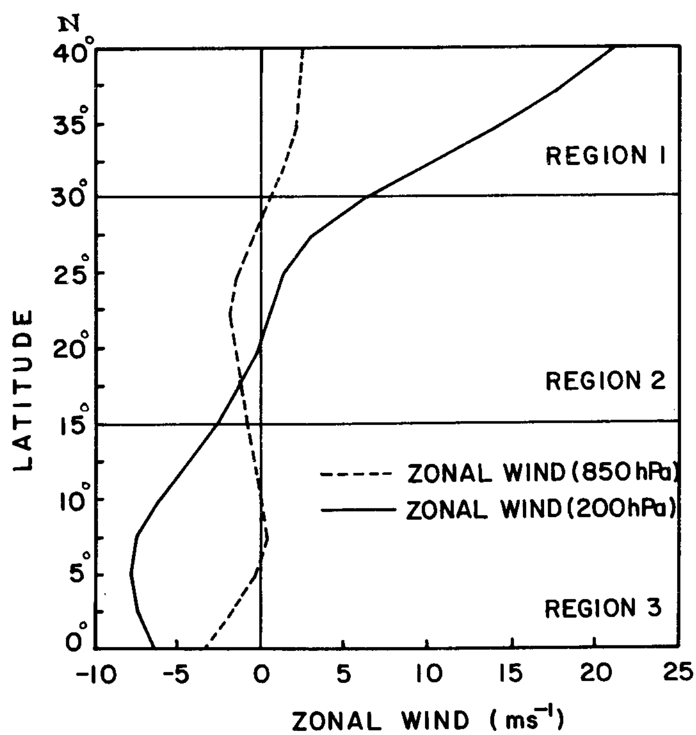

Figure 2. Zonal average of time averaged (June – August, 1991) zonal wind at 200 hPa and 850 hPa. (Unit: $m^2 s^{-1}$).

dividing the global area between the equator and 40°N into three latitudinal spans as follows:

Region 1 (40°N to 30°N): This is the region of westerlies (positive zonal wind, figure 2) at both levels.

Region 2 (30°N to 15°N): Over this region both easterlies and westerlies are present at 200 hPa and mostly easterlies at 850 hPa.

Region 3 (15°N to Equator): This is the region of easterlies at both levels.

Hereafter Regions 1, 2 and 3 will be referred as R1, R2 and R3 respectively.

Thus R1 will present energetics over a region of westerlies, R3 will present energetics over a region of easterlies while R2 will present energetics over a region containing easterlies as well as westerlies for 200 hPa. Such a division is necessary to avoid compounding of circulation patterns of different characters.

4.1 *Latitudinal variation of transport of momentum*

Figure 3 gives latitudinal variation of transport of momentum by Transient Eddies (TE), Standing Eddies (SE) and Mean Meridional Circulation (MMC) at 200 hPa. A positive (negative) sign indicates northward (southward) transport. The transport of momentum by MMC is significant over R3 and insignificant over R2 and R1. The transport of momentum by TE is less over R3, gradually increases over R2 and

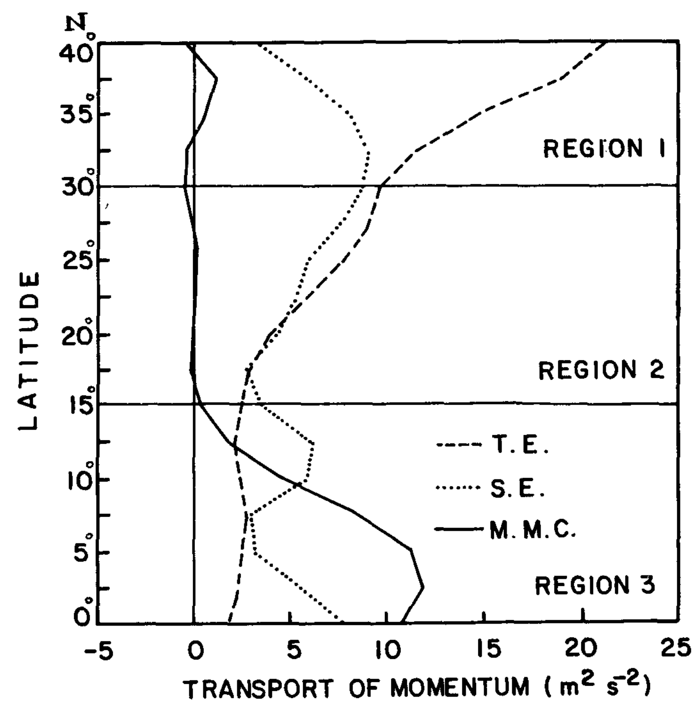

Figure 3. Transport of momentum by Transient Eddies (TE), Standing Eddies (SE) and Mean Meridional Circulation (MMC) at 200 hPa during June – August 1991. (Unit: $m^2 s^{-2}$).

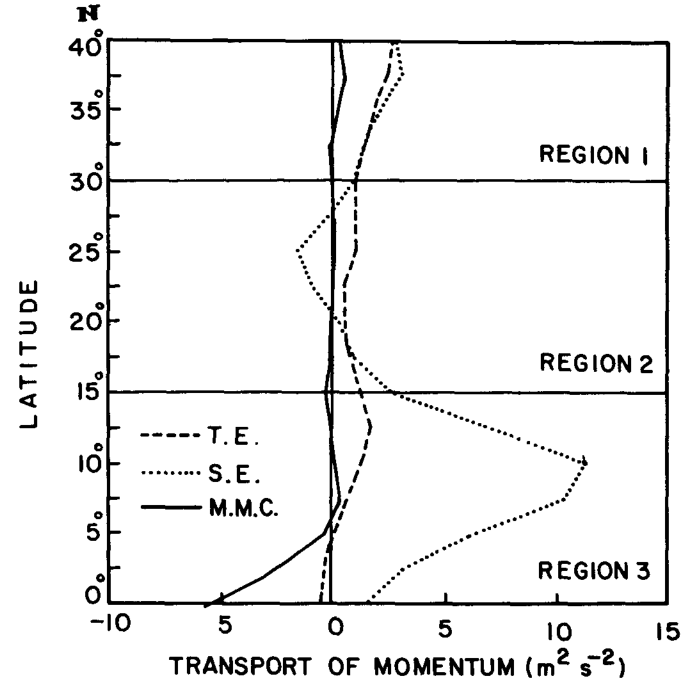

Figure 4. Transport of momentum by Transient Eddies (TE), Standing Eddies (SE) and Mean Meridional Circulation (MMC) at 850 hPa during June – August 1991. (Unit: $m^2 s^{-2}$).

dominates over R1 as compared to transport of momentum by SE. Krishnamurti (1981) and Murakami (1981) have observed similar features at 200 hPa.

At 850 hPa (figure 4) the transport of momentum by SE is significantly high over R3 and is maximum around 10°N. The low level westerly jet, which persists over the Indian sub-continent throughout the monsoon season, might be one of the reasons for the dominating features of SE over R3 at 850 hPa. The transport of momentum by MMC is southward between the equator and 5°N and is almost insignificant over the remaining area; and by TE (except between equator and 2·5°N) it is northward.

4.2 *Summer mean energetics of individual waves*

The transport of momentum $\langle J(n)\rangle$, Kinetic energy $\langle K(n)\rangle$, wave to zonal mean flow interaction $\langle M(n)\rangle$ and wave-to-wave interaction $\langle L(n)\rangle$ are computed for each day from 1st June 1991 to 31st August 1991 by using daily data and their time means are presented in tables 1 to 4.

4.2.1 *Transport of westerly momentum* $\langle J(n)\rangle$: The transport of momentum plays an important role in the exchange of kinetic energy between the eddies and zonal mean flow. The positive (negative) sign of $J(n)$ indicates northward (southward) transport of momentum by wave n.

At 200 hPa (table 1) all waves (except wave number 4 over R1, wave number 5 over R2 and wave number 10 over R3) transport momentum northward. Wave number

Table 1. Wavewise distribution of meridional transport of westerly momentum, $J(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $m^2 s^{-2}$).

Wave number n	200 hPa			850 hPa		
	R1	R2	R3	R1	R2	R3
1	2·81	0·79	3·60	0·38	0·98	7·29
2	3·03	4·54	1·99	1·59	0·10	1·08
3	8·62	1·79	1·21	1·26	−0·02	0·10
4	−0·23	1·75	0·56	−0·74	−0·19	0·01
5	1·58	−0·38	0·21	0·05	0·20	0·56
6	0·54	0·03	0·26	0·65	0·46	0·53
7	4·33	0·38	0·47	−0·11	−0·15	0·25
8	2·33	0·83	0·18	0·41	0·05	0·17
9	2·69	1·26	0·24	0·24	−0·30	0·25
10	1·13	1·25	−0·05	0·10	−0·17	0·20
1 to 4	14·23	8·86	7·36	2·48	0·88	8·48
5 to 10	12·60	3·37	1·30	1·35	0·09	1·97
1 to 10	26·83	12·23	8·66	3·83	0·97	10·46

Table 2. Wavewise distribution of kinetic energy, $K(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $m^2 s^{-2}$).

Wave number n	200 hPa			850 hPa		
	R1	R2	R3	R1	R2	R3
1	24·77	41·18	27·16	3·33	9·79	20·69
2	12·58	14·68	8·50	3·49	5·34	6·34
3	18·93	10·19	4·58	3·31	1·69	1·61
4	8·90	7·34	4·25	2·55	2·14	2·17
5	8·97	4·46	2·97	2·25	1·63	1·74
6	13·41	6·13	2·27	2·88	1·91	1·29
7	13·03	4·95	2·55	2·38	1·52	1·21
8	8·18	4·35	2·09	1·45	1·29	0·88
9	7·98	2·20	1·80	1·60	1·29	0·91
10	5·58	4·29	1·44	1·09	0·97	0·77
1 to 4	65·17	73·38	44·49	12·69	18·97	30·81
5 to 10	57·15	28·38	13·11	11·64	8·63	6·81
1 to 10	122·32	101·77	57·60	24·33	27·59	37·62

1 over R3, wave number 2 over R2 and wave number 3 over R1 dominate the spectrum of transport of momentum. The dominance of wave number 1 over R3 and wave number 2 over R2 can be well understood from figure 1(a) which gives the mean (Ψ) field at 200 hPa. Half of the east-west part over R3 is covered by easterlies and the remaining half by westerlies. These are the features of wave number 1, hence we have the dominance of wave number 1 over R3. Over R2 anticyclonic circulations over Tibet and Mexico and two troughs over mid-Pacific and mid-Atlantic exhibit the features of wave number 2 and therefore the transport over R2 is dominated by wave 2. Moreover, the oceanic troughs have large NE-SW tilt which results in the northward transport of momentum.

Table 3. Wavewise distribution of wave-to-zonal interactions, $M(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $10^{-6} m^2 s^{-3}$).

Wave number n	200 hPa			850 hPa		
	R1	R2	R3	R1	R2	R3
1	−35·20	−1·09	−19·30	−1·05	1·48	−0·59
2	−35·78	−22·50	−12·04	−5·61	−0·84	1·05
3	−125·53	−12·98	−7·09	−3·68	0·15	0·70
4	1·33	−9·22	−6·12	2·12	1·12	2·13
5	−23·16	−0·17	−2·52	−0·52	0·86	0·70
6	−6·63	3·82	−2·40	−2·07	−0·37	1·48
7	−53·00	−3·89	−5·04	−0·39	0·81	1·70
8	−30·27	−3·60	−3·08	−1·58	−0·03	0·26
9	−37·89	−7·29	−3·58	−0·98	0·76	0·55
10	−11·94	−3·36	−2·15	−0·51	0·45	0·68
1 to 4	−195·19	−45·77	−44·55	−8·22	1·91	3·29
5 to 10	−162·89	−14·49	−18·76	−6·05	2·49	5·37
1 to 10	−358·08	−60·26	−63·31	−14·27	4·40	8·66

Table 4. Wavewise distribution of wave-to-wave interactions, $L(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $10^{-6} m^2 s^{-3}$).

Wave number n	200 hPa			850 hPa		
	R1	R2	R3	R1	R2	R3
1	−74·54	11·35	−30·87	−9·94	4·51	−16·93
2	−2·75	−95·53	−10·21	0·85	7·42	−3·72
3	48·96	56·73	−5·74	−4·36	−0·17	−2·24
4	39·12	−14·37	−0·28	−3·44	−4·67	4·94
5	30·87	11·97	1·20	−0·24	3·29	−4·27
6	26·07	−4·71	−3·95	−6·64	−2·97	0·86
7	−11·80	16·38	−1·26	−4·36	−1·45	1·45
8	10·78	15·04	−1·56	1·52	−1·75	−1·20
9	22·35	4·12	2·71	−2·83	2·56	−0·94
10	3·45	−6·09	−1·27	0·81	−0·68	−0·53
1 to 4	10·80	−41·82	−47·11	−16·89	16·43	−17·96
5 to 10	81·73	36·72	−4·12	−11·72	−1·00	−4·63
1 to 10	92·52	−5·10	−51·23	−28·62	15·43	−22·59

At 850 hPa (table 1), the transport of momentum by wave number 1 over R3 not only dominates over all the three regions but also has a larger contribution than all other waves (except wave number 3 over R1) at 200 hPa. The transport of momentum is insignificant over R2.

The sum of waves 1 to 10 show that at both levels, the transport of momentum is northward and over R1 and R2 it is one order higher in magnitude at 200 hPa.

4.2.2 *Kinetic energy* $\langle K(n) \rangle$: At 200 hPa (table 2) wave number 1 dominates the spectrum of kinetic energy over all the regions. Wave numbers 6 and 7 over R1 have significant kinetic energy. The contribution of small scale eddies (wave numbers 5 to 10) gradually increases from R3 to R1. This indicates that small scale eddies intensify northward.

Our values of $\langle K(n) \rangle$ at 200 hPa are larger (particularly for wave numbers 1 and 2) over R2 and R3 than that of Murakami (1981). This is because Murakami has presented the mean energetics of three years viz. 1970–72. The year 1972 was a typical drought monsoon year. Bawiskar and Singh (1992) found that the kinetic energy of waves (particularly of wave numbers 1 and 2) is less during the drought monsoon years as compared to the normal monsoon years. Therefore in the mean picture of three years the kinetic energy of waves might have suppressed. Over R1 our $\langle K(n) \rangle$ values are smaller. It is because this region in Murakami's study is about 5° larger than the one in our case.

At 850 hPa (table 2) wave number 1 over R3 has the maximum kinetic energy. All the waves (wave numbers 1 to 10) over R1 have comparable kinetic energy. Like 200 hPa, the small scale eddies intensify northward.

The sum of waves 1 to 10 is one order higher over R1 and R2 at 200 hPa as compared to 850 hPa.

4.2.3 *Wave to zonal mean flow interaction,* $\langle M(n) \rangle$: The negative (positive) sign of $M(n)$ indicates that wave number n is source (sink) of kinetic energy to zonal mean flow. At 200 hPa (table 3), $M(n)$ is negative for all waves (except wave number 6 over R2 and wave number 4 over R1). This indicates that all waves between the equator and 40°N are sources of kinetic energy to zonal mean flow. This can be explained with the help of equation (3·6). The first term of RHS of equation (3·6) dominates over the other two terms as one of the factors of the first term is $[u]$ whereas for the other two terms it is $[v]$. Generally $[u]$ is much larger than $[v]$. The first term is the product of the transport of momentum and gradient of $[u]$. We have also seen in section 4.2.1 that transport of momentum is positive. From figure 2 it can be seen that the zonal average of zonal wind has an anticyclonic shear so the gradient of $[u]$ is positive. Thus the first term is positive and the negative sign outside the main bracket results is negative $\langle M(n) \rangle$. Wave number 3 over R1 is the major source of kinetic energy to zonal mean flow. The sum of wave numbers 1 to 10 over R1 is one order higher than the sum over R2 and R3. It is mainly due to the stronger gradient of $[u]$ over R1 (figure 2).

The direction of $\langle M(n) \rangle$ interaction in our case is almost similar (except wave number 6 over R2 and wave number 4 over R1) to that of Murakami (1981), and most of the waves over R1 and R3 have a larger contribution. In some cases, for example wave numbers 1 and 2 over R3 and wave number 3 over R1 are one order higher, while waves over R2 have a smaller contribution as compared to Murakami's results. This is because an individual year can be anomalous with respect to average conditions.

At 850 hPa (table 3), the zonal mean flow is a source of kinetic energy to most of the waves over R2 and R3. Thus the exchange of kinetic energy between the waves and zonal mean flow over R2 and R3 is reverse as compared to the exchange at 200 hPa. From figure 2 we find that the gradient of zonal wind over R2 and R3 is positive at 200 hPa and almost negative at 850 hPa. Therefore, the exchange of kinetic energy at two levels is opposite. Waves are sources of kinetic energy to zonal mean flow over R1.

The north-south gradient of zonal wind (figure 2) at 200 hPa is stronger than the gradient at 850 hPa and hence $M(n)$ interactions at 200 hPa are one order higher.

4.2.4 *Wave-to-wave interaction,* $\langle L(n) \rangle$: The negative (positive) sign indicates that wave number n is a source (sink) of kinetic energy to all other waves. At 200 hPa (table 4), wave number 1 over R1 and R3 and wave number 2 over R2 are major sources of kinetic energy to all other waves.

Our results of $\langle L(n) \rangle$ are fairly in agreement with the results of Murakami (1981). Over R2, wave number 1 is a sink and wave number 2 is a major source of kinetic energy to other waves in both the studies. Wavewise, there are some differences. Murakami pointed out in the same study that as far as $L(n)$ processes are concerned an individual year can be highly anomalous with respect to average conditions.

At 850 hPa (table 4), wave number 1 over R1 and R3 and wave numbers 6 and 7 over R1 have a significant contribution. Interestingly, over R2, wave numbers 1 and 2 are sinks of kinetic energy, while wave numbers 6, 7 and 8 are sources of kinetic energy to other waves.

Theoretically $L(n)$ summed over all the eddies should vanish. This is possible when $L(n)$ processes are integrated over the whole globe. When a limited area is considered, as in the present study, the sum need not necessarily be zero. The negative sum (surplus kinetic energy) over a region indicates that eddies over that region transport kinetic energy to the eddies over a region having a positive sum (deficit kinetic energy). Table 4 shows that at 200 hPa eddies over R2 and R3 transport kinetic energy to the eddies over R1 and at 850 hPa eddies over R1 and R3 maintain eddies over R2.

4.3 *Transient and standing components*

The contribution of transient, standing and standing-transient components is presented in tables 5 to 10.

4.3.1 *Transport of momentum*: At 200 hPa (table 5), we find that for long waves (wave numbers 1 to 4) the standing part $J2(n)$ is greater than the transient part $J1(n)$ over all the three regions and for short waves (wave numbers 5 to 10), $J1(n)$ is greater than $J2(n)$. This indicates that transport of momentum for long waves is dominated by the standing part and for short waves it is dominated by the transient part.

At 850 hPa (table 5), the standing part of wave number 1 over R3 contributes nearly 96% of the total contribution indicating that the standing wave number 1 dominates the circulation at 850 hPa over R3 and its major cause might be the low level westerly jet over the Indian sub-continent.

4.3.2 *Kinetic energy*: Table 6 gives the transient and standing components of kinetic energy of wave number n. At 200 hPa the kinetic energy of the standing and transient waves shows a similar trend as seen in the case of the transport of momentum i.e. the standing part (except over R1) dominates the long waves and the transient part dominates the short waves. Murakami (1981) has also found that for short waves the transient part dominates over the standing part. This emphasises the important role of small scale eddies at 200 hPa during the monsoon season. The spectrum of $K1(n)$ over R1 shows a primary maxima for wave number 3 and the secondary maxima for wave number 6. Comparison of $K1(n)$ and $K2(n)$ over R2 and R3 with that of Murakami indicates that the standing component is mainly responsible for high kinetic energy in our case.

At 850 hPa (table 6) the kinetic energy almost follows the pattern of dominance of the standing part for wave numbers 1 and 2 and dominance of the transient part for wave numbers 3 to 10.

Table 5. Wavewise distribution of transport of momentum, $J1(n)$ and $J2(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $m^2 s^{-2}$).

Wave number	200 hPa						850 hPa					
	R1		R2		R3		R1		R2		R3	
n	$J1(n)$	$J2(n)$	$J1(n)$	$J2(n)$	$J1(n)$	$J2(n)$	$J1(n)$	$J2(n)$	$J1(n)$	$J2(n)$	$J1(n)$	$J2(n)$
1	1·05	1·76	−0·05	0·83	0·53	3·07	0·23	0·15	0·20	0·78	0·29	7·00
2	0·27	2·77	0·73	3·81	0·68	1·31	0·17	1·42	0·06	0·04	0·07	1·02
3	3·32	5·29	0·42	1·37	0·31	0·89	0·18	1·07	0·16	−0·18	0·04	0·07
4	−0·32	0·09	0·68	1·06	0·51	0·06	0·02	−0·77	0·16	−0·35	0·21	−0·20
5	1·05	0·54	−0·09	−0·29	0·03	0·18	−0·03	0·08	0·05	0·15	0·12	0·44
6	1·63	−1·09	0·58	−0·55	0·17	0·09	0·50	0·15	0·16	0·29	0·09	0·44
7	3·26	1·07	0·70	−0·31	0·44	0·03	0·15	−0·26	0·05	−0·20	0·07	0·18
8	2·34	−0·01	0·87	−0·05	0·08	0·09	0·34	0·07	0·06	−0·01	0·04	0·14
9	2·38	0·31	1·22	0·04	0·30	−0·06	0·29	−0·05	0·03	−0·34	0·06	0·19
10	1·25	−0·12	1·34	−0·09	−0·02	−0·03	0·09	0·01	0·00	−0·17	0·04	0·16
1 to 4	4·32	9·91	1·79	7·07	2·03	5·33	0·61	1·88	0·58	0·30	0·60	7·89
5 to 10	11·90	0·69	4·62	−1·25	1·00	0·30	1·34	0·01	0·36	−0·27	0·42	1·55
1 to 10	16·22	10·60	6·41	5·82	3·03	5·64	1·94	1·89	0·94	0·03	1·01	9·44

Table 6. Wavewise distribution of kinetic energy, $K1(n)$ and $K2(n)$ at 200 and 850 hPa for the period June through August 1991. (Unit: $m^2 s^{-2}$).

Wave number	200 hPa						850 hPa					
	R1		R2		R3		R1		R2		R3	
n	$K1(n)$	$K2(n)$	$K1(n)$	$K2(n)$	$K1(n)$	$K2(n)$	$K1(n)$	$K2(n)$	$K1(n)$	$K2(n)$	$K1(n)$	$K2(n)$
1	11·69	13·08	7·87	33·32	4·51	22·65	1·57	1·76	1·68	8·11	1·89	18·80
2	8·11	4·47	5·96	8·72	3·31	5·19	1·59	1·90	1·20	4·14	1·21	5·13
3	12·61	6·31	5·72	4·46	3·28	1·30	1·73	1·59	1·17	0·52	0·94	0·67
4	7·91	0·99	4·74	2·60	2·87	1·38	1·66	0·89	1·19	0·94	1·09	1·07
5	7·89	1·08	3·95	0·51	2·38	0·59	1·41	0·84	1·24	0·40	0·78	0·96
6	12·04	1·37	4·94	1·20	1·95	0·32	1·90	0·98	1·20	0·71	0·62	0·67
7	10·79	2·24	4·26	0·69	2·24	0·32	1·35	1·03	0·89	0·63	0·55	0·67
8	7·56	0·62	4·02	0·34	1·93	0·16	1·30	0·14	0·88	0·42	0·50	0·38
9	7·30	0·68	3·97	0·23	1·62	0·18	1·29	0·31	0·78	0·51	0·41	0·50
10	5·40	0·18	3·99	0·30	1·36	0·08	0·84	0·25	0·67	0·30	0·37	0·40
1 to 4	40·33	24·84	24·28	49·10	13·97	30·52	6·55	6·14	5·24	13·72	5·14	25·67
5 to 10	50·97	6·18	25·12	3·26	11·47	1·64	8·09	3·55	5·65	2·97	3·24	3·57
1 to 10	91·30	31·02	49·40	52·36	25·44	32·16	14·64	6·69	10·89	16·70	8·37	29·24

4.3.3 *Wave to zonal mean flow interaction*: The contributions of four components of $\langle M(n) \rangle$ as explained in Appendix I are given in tables 7 and 8 for 200 hPa and 850 hPa respectively.

At 200 hPa (table 7) the sum of waves 1 to 10 for $M1(n)$ is larger than $M3(n)$ over R2 and R3 and substantially larger over R1 indicating that time-averaged zonal mean flow receives the major part of kinetic energy from transient waves mainly through short transient waves.

At 850 hPa (table 8) the sum of waves 1 to 10 for $M1(n)$ and $M3(n)$ over R2 and R3 is positive indicating that at 850 hPa both standing and transient waves receive kinetic energy from time-averaged zonal mean flow, this is exactly opposite to what happens at 200 hPa.

4.4.4 *Wave-to-wave interactions*: The contributions of four components of $\langle L(n) \rangle$ for 200 and 850 hPa are given in tables 9 and 10 respectively.

At 200 hPa (table 9) the sum of waves 1 to 10 for $L3(n)$ over all the three regions is negative indicating that the standing waves are sources of kinetic energy to transient waves via standing to transient wave-to-wave interaction. $L4(n)$ over all three regions indicates that long standing waves are sources of kinetic energy to short standing waves. These features are observed in most of the earlier studies (Murakami 1981; Krishnamurti and Kanamitsu 1981) at 200 hPa indicating the adequacy of data and method applied.

At 850 hPa (table 10), the sum of waves 1 to 10 for $L3(n)$ is negative over all the three regions, which is similar to the trend observed at 200 hPa. But for $L4(n)$ over R1 and R3 short standing waves are also sources of kinetic energy to other waves which is not the case at 200 hPa.

It can be seen from tables 1 to 10 that equation (A18) in Appendix I is satisfied, which confirms the validity of the procedure applied in partitioning the equations (3·4) to (3·7) into standing, transient and standing-transient components.

Table 7. Wave-to-zonal mean flow interactions for $M1(n)$, $M2(n)$, $M3(n)$ and $M4(n)$ at 200 hPa for the period June through August 1991. (Unit: $10^{-6}\,m^2 s^{-3}$).

Wave number	R1				R2				R3			
n	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$
1	−16·34	1·20	−23·43	3·37	0·47	−2·30	−3·65	4·40	−2·94	−0·86	−13·90	−1·60
2	−2·91	3·37	−36·41	−0·19	−3·46	−1·46	−17·14	−0·43	−3·55	−0·14	−7·18	−1·17
3	−49·78	7·47	−78·20	−5·02	−2·34	−0·99	−6·74	−2·91	−3·15	0·30	−4·11	−0·13
4	4·62	−1·25	−0·73	−1·31	−2·77	−1·48	−4·44	−0·53	−3·75	−2·17	−1·25	1·05
5	−15·56	1·64	−8·21	−1·02	−0·29	−0·55	1·13	−0·46	−2·18	−0·17	−0·16	−0·02
6	−24·61	2·63	14·13	1·22	−2·77	1·98	3·28	1·34	−2·70	0·53	−0·53	0·30
7	−47·74	11·14	−16·61	0·22	−4·22	−0·87	1·04	0·35	−4·81	−0·03	−0·30	0·10
8	−34·58	4·27	0·03	0·01	−4·47	0·71	0·37	−0·21	−3·06	0·32	−0·39	0·05
9	−34·60	1·03	−4·50	0·18	−5·92	−0·84	−0·37	−0·16	−3·52	−0·14	0·04	0·04
10	−17·45	3·07	1·47	0·97	−5·90	1·61	0·56	0·37	−1·72	−0·31	−0·06	−0·05
1 to 4	−64·42	11·16	−138·77	−3·15	−8·10	−6·23	−31·99	0·54	−13·39	−2·87	−26·44	−1·85
5 to 10	−174·55	23·77	−13·69	1·58	−23·77	2·04	6·01	1·23	−17·99	0·20	−1·39	0·41
1 to 10	−238·97	34·93	−152·46	−1·57	−31·87	−4·19	−25·97	1·77	−31·37	−2·67	−27·84	−1·44

Table 8. Wave-to-zonal mean flow interactions for $M1(n)$, $M2(n)$, $M3(n)$ and $M4(n)$ at 850 hPa for the period June through August 1991. (Unit: $10^{-6}\,m^2\,s^{-3}$).

Wave number	R1				R2				R3			
n	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$	$M1(n)$	$M2(n)$	$M3(n)$	$M4(n)$
1	−0·68	0·06	−0·21	−0·23	0·24	−0·33	1·89	−0·32	1·21	−0·57	−0·13	−1·11
2	−0·56	−0·36	−4·18	−0·51	0·09	−0·88	0·49	−0·53	0·65	0·30	0·11	−0·01
3	−0·66	0·18	−3·29	0·10	0·17	0·02	−0·19	0·14	0·54	0·32	−0·13	−0·03
4	−0·36	0·36	2·03	0·09	0·34	−0·52	0·85	0·46	0·76	0·00	1·15	0·21
5	−0·07	−0·62	−0·21	0·37	0·62	0·03	0·21	0·01	0·54	−0·09	0·31	−0·06
6	−1·79	0·35	−0·64	0·01	0·02	−0·30	0·03	−0·12	0·58	−0·06	0·92	0·03
7	−0·73	−0·03	0·43	−0·06	0·27	−0·40	0·84	0·10	0·47	−0·09	1·23	0·08
8	−1·18	0·00	−0·31	−0·08	0·16	0·03	−0·24	0·02	0·42	−0·09	0·00	−0·07
9	−1·01	−0·15	0·14	0·05	0·12	0·13	0·50	0·00	0·42	−0·06	0·21	−0·02
10	−0·45	0·08	−0·05	−0·09	0·32	0·13	0·07	−0·07	0·46	0·03	0·22	−0·03
1 to 4	−2·26	0·24	−5·65	−0·55	0·84	−1·72	3·04	−0·25	3·16	0·07	1·00	−0·94
5 to 10	−5·23	−0·39	−0·64	0·20	1·50	−0·37	1·41	−0·06	2·90	−0·34	2·89	−0·07
1 to 10	−7·48	−0·15	−6·28	−0·35	2·34	−2·08	4·45	−0·31	6·05	−0·28	3·89	−1·01

Table 9. Wave-to-wave interactions for $L1(n)$, $L2(n)$, $L3(n)$ and $L4(n)$ at 200 hPa for the period June through August 1991. (Unit: $10^{-6}\,m^2 s^{-3}$).

Wave number	R1				R2				R3			
n	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$
1	−10·81	−15·20	−8·04	−40·49	−3·30	0·62	−8·76	22·78	0·64	−1·06	2·74	−33·20
2	13·60	−4·63	11·28	−22·99	−2·02	−6·47	−10·44	−76·60	−0·23	0·23	−6·25	−3·96
3	22·97	−16·32	8·41	33·91	14·59	4·18	−9·33	47·30	0·09	1·95	−2·60	−5·17
4	9·71	10·63	1·36	17·42	1·43	−1·58	−4·11	−10·12	−0·18	1·68	−1·20	−0·59
5	−12·01	37·21	−4·75	10·43	14·13	−4·53	−1·96	4·33	−0·98	−0·03	−0·26	2·73
6	11·26	2·83	0·25	11·73	−6·23	6·09	−2·87	−1·71	−2·03	−0·93	−1·09	0·11
7	5·61	−4·68	−9·79	−2·93	−6·60	5·80	4·19	12·98	−0·87	1·53	−0·12	−1·81
8	−7·11	16·09	−2·59	4·39	11·30	3·87	−0·22	0·09	−1·08	−0·77	−0·48	0·77
9	13·66	16·58	−1·48	−6·42	7·94	−5·84	0·38	1·63	0·49	0·27	0·22	1·74
10	4·53	−3·25	0·73	1·44	−0·05	−4·85	0·06	−1·25	−0·28	0·02	−0·16	−0·84
1 to 4	35·47	−25·54	13·01	−12·15	10·69	−3·24	−32·64	−16·63	0·32	2·80	−7·31	−42·92
5 to 10	15·94	64·78	−17·64	18·64	20·51	0·55	−0·41	16·07	−4·76	−0·19	−1·90	2·27
1 to 10	51·41	39·22	−4·62	6·49	31·20	−2·70	−33·05	−0·56	−4·44	2·61	−9·20	−40·21

Table 10. Wave-to-wave interactions for $L1(n)$, $L2(n)$, $L3(n)$ and $L4(n)$ at 850 hPa for the period June through August 1991. (Unit: $10^{-6}\,m^2 s^{-3}$).

Wave number	R1				R2				R3			
n	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$	$L1(n)$	$L2(n)$	$L3(n)$	$L4(n)$
1	−0·68	−0·87	−4·34	−4·05	1·29	−1·50	−7·89	12·61	0·70	−0·82	−8·80	−8·01
2	−0·58	0·58	−1·83	2·67	−0·10	−0·22	−1·91	9·66	1·57	−1·38	−5·15	1·24
3	0·01	−1·89	−1·73	−0·74	0·37	−0·11	0·40	−0·84	1·12	−0·59	−0·32	−2·46
4	0·79	−0·58	−1·77	−1·88	0·83	−1·99	1·46	4·36	−0·08	−1·01	0·33	5·70
5	0·55	−0·91	2·10	−1·97	0·76	−1·06	0·21	3·39	1·11	0·04	−1·21	−4·23
6	−3·13	0·29	−0·07	−3·72	0·17	−0·49	−1·46	−1·19	−0·19	−0·28	−0·74	2·07
7	−1·83	−0·55	0·56	−2·54	−0·29	−0·64	−0·51	−0·01	0·56	0·24	−0·42	1·06
8	0·03	1·55	−0·50	0·45	−1·26	0·04	−0·43	−0·09	0·05	0·70	−0·42	−1·53
9	−0·68	−0·53	−0·66	−0·97	1·36	0·41	−0·36	1·15	0·68	0·03	−0·36	−1·30
10	1·39	−0·06	−0·23	−0·28	0·28	0·50	−0·19	−1·28	1·44	0·31	−0·06	−2·21
1 to 4	−0·46	−2·76	−9·67	−4·00	2·39	−3·82	−7·93	25·79	3·32	−3·80	−13·95	−3·53
5 to 10	−3·68	−0·21	1·20	−9·03	1·01	−1·24	−2·74	1·97	3·67	1·04	−3·20	−6·13
1 to 10	−4·14	−2·97	−8·47	−13·04	3·40	−5·06	−10·67	27·76	6·98	−2·76	−17·15	−9·66

5. Concluding remarks

The salient features that emerged from this study are briefly summarized as follows:

5.1 *Important findings of 200 hPa*

- Transport of momentum is dominated by transient eddies over R1 (30°N to 40°N).
- Wave number 1 over R3 (equator to 15°N), wave number 2 over R2 (15°N to 30°N) and wave number 3 over R1 dominate the spectrum of transport of momentum and wave to zonal mean flow interaction.
- Wave number 1 over R1 and R3 and wave number 2 over R2 are major sources of kinetic energy to other waves viz., wave-to-wave interaction.

5.2 *Important findings of 850 hPa*

- Transport of momentum is dominated by standing eddies over R3.
- Wave number 1 over R3 has maximum contribution in the spectrum of transport of momentum and kinetic energy and more than 90% of its contribution is from the standing component.

5.3 *Circulation pattern of 200 hPa and 850 hPa*

The circulation patterns of 200 hPa and 850 hPa are found to be almost opposite in character. However, there are a number of energy processes that exhibit similar characteristics and some of them exhibit contrasting behaviour.

(A) *Similar energy processes at 200 hPa and 850 hPa*

- Transport of momentum by most of the waves is northward.
- Small scale eddies intensify northward.
- Eddies are sources of kinetic energy to zonal mean flow over R1.
- $L(n)$ interactions display similar behaviour over R3.
- Transport of momentum and kinetic energy of long waves are dominated by the standing component and for short waves transient component is dominant.
- Standing waves are sources of kinetic energy to transient waves via standing to transient wave-to-wave interaction.

(B) *Contrasting energy processes of two levels*

- Over R2 and R3 most of the standing and transient eddies are sources of kinetic energy to zonal mean flow at 200 hPa, while at 850 hPa the zonal mean flow is a source of kinetic energy to standing and transient eddies.
- Sum of waves 1 to 10 of $L(n)$ interaction shows that at 200 hPa waves over R2 maintain waves over R1, while at 850 hPa waves over R1 maintain waves over R2.

5.4 *Important role of zonal mean of zonal wind*

The study further shows that the north-south gradient of the zonal mean of zonal wind is the deciding factor of $M(n)$ interaction.

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Appendix I

Partitioning of equations (3.4) to (3.7) into standing and transient wave components.

Daily u and v data were separated into time mean and transient component. For example u was expressed as:

$$u = \langle u \rangle + u^* \tag{A1}$$

where $\langle u \rangle$ and u^* are time mean and transient component of u respectively.

On substituting equation (A1) in equation (3.2), we get

$$U(n) = \frac{1}{2\pi}\int_0^{2\pi} (\langle u \rangle + u^*) e^{-in\lambda} \mathrm{d}\lambda. \tag{A2}$$

Let $U_s(n)$ and $U_t(n)$ be the spectral functions of $\langle u \rangle$ and u^*, we get

$$U(n) = U_s(n) + U_t(n). \tag{A3}$$

Substitution of equation (A3) in equation (3.4) gives four distinct components. Out of which two components become zero when their time averages are taken. Two non-zero components are:

$$J1(n) = \langle \gamma_{u^*v^*} \rangle, \tag{A4}$$

$$J2(n) = \gamma_{\langle u \rangle \langle v \rangle}, \tag{A5}$$

where,

$J1(n)$ = Transport of westerly momentum by transient eddy of wave number n

$J2(n)$ = Transport of westerly momentum by standing eddy of wave number n.

On substituting equation (A3) in equation (3.5), we get three terms viz., (i) kinetic energy of transient wave, (ii) kinetic energy of standing wave and (iii) kinetic energy of transient-standing wave. When the time average is taken, the third term becomes zero. The first two terms can be written as:

$$K1(n) = \langle |U_t(n)|^2 + |V_t(n)|^2 \rangle, \tag{A6}$$

$$K2(n) = |U_s(n)|^2 + |V_s(n)|^2, \tag{A7}$$

where,

$K1(n)$ = Kinetic energy of transient eddy of wave number n.

$K2(n)$ = Kinetic energy of standing eddy of wave number n.

The energy equation for $K1(n)$ and $K2(n)$ may be written approximately as follows:

$$\frac{\partial K1(n)}{\partial t} = M1(n) + M2(n) + L1(n) + L2(n) + C1(n), \tag{A8}$$

$$\frac{\partial K2(n)}{\partial t} = M3(n) + M4(n) + L3(n) + L4(n) + C2(n). \tag{A9}$$

The term related to friction is omitted. The various terms in equations (A8) and (A9) can be derived as follows:

On substituting equation (A3) in equation (3.6), we get eight components out of which three components become zero on their time average. Out of the remaining five components, two components are added resulting in the following four distinct components as:

$$M1(n) = -\left(\left\langle \gamma_{u^*v^*} \cos\phi \left(\frac{[\langle u\rangle]}{\cos\phi}\right)_\phi + 2\alpha_{v^*v^*}([\langle v\rangle])_\phi - 2\alpha_{u^*u^*}[\langle v\rangle]\frac{\tan\phi}{a}\right\rangle\right), \tag{A10}$$

$$M2(n) = -\left(\left\langle (\gamma_{u^*v^*} + \gamma_{u^*\langle v\rangle})\cos\phi \left(\frac{[u^*]}{\cos\phi}\right)_\phi + 2(\alpha_{v^*v^*} + \alpha_{v^*\langle v\rangle}([v^*])_\phi - 2(\alpha_{u^*u^*} + \alpha_{u^*\langle u\rangle}[v^*]\frac{\tan\phi}{a}\right\rangle\right), \tag{A11}$$

$$M3(n) = -\left(\gamma_{\langle u\rangle\langle v\rangle} \cos\phi \left(\frac{[\langle u\rangle]}{\cos\phi}\right)_\phi + 2\alpha_{\langle v\rangle\langle v\rangle}([\langle v\rangle])_\phi - 2\alpha_{\langle u\rangle\langle u\rangle}[\langle v\rangle]\frac{\tan\phi}{a}\right), \tag{A12}$$

$$M4(n) = -\left(\left\langle \gamma_{\langle u\rangle v^*} \cos\phi \left(\frac{[\langle u^*\rangle]}{\cos\phi}\right)_\phi + 2\alpha_{\langle v\rangle v^*}([\langle v^*\rangle])_\phi - 2\alpha_{\langle u\rangle u^*}[\langle v^*\rangle]\frac{\tan\phi}{a}\right\rangle\right). \tag{A13}$$

Interpretation of the four components of $M(n)$ can be given as below:

In $M1(n)$, time averaged zonal mean flows interact with transient eddies, therefore this represents interaction between time averaged zonal mean flows and transient wave n.

In $M2(n)$, transient zonal mean flows interact with transient and standing eddies, therefore this represents interaction between transient zonal mean flows and transient and standing eddies of wave number n.

In $M3(n)$, time averaged zonal mean flows interact with standing eddies, therefore this represents interaction between time averaged zonal mean flows and standing wave n.

In $M4(n)$, transient zonal mean flows interact with standing and transient eddies therefore this represents interaction between transient zonal mean flows and standing and transient eddies of wave number n.

Similarly four components of equation (3.7) are:

$$L1(n) = -\Bigg(\Bigg\langle \sigma(\langle u\rangle \beta_{u^*u^*} + u^*\beta_{u^*\langle u\rangle} + \langle v\rangle \beta_{v^*u^*} + v^*\beta_{v^*\langle u\rangle}) + (\langle u\rangle)_\phi \beta_{u^*v^*} + (u^*)_\phi \beta_{u^*\langle v\rangle} + (\langle v\rangle)_\phi \beta_{v^*v^*} + (v^*)_\phi \beta_{v^*\langle v\rangle} + \frac{\tan\phi}{a}(\langle u\rangle \beta_{v^*u^*} + u^*\beta_{v^*\langle u\rangle} - \langle v\rangle \beta_{u^*u^*} - v^*\beta_{u^*\langle u\rangle})\Bigg\rangle\Bigg), \tag{A14}$$

$$L2(n) = -\Bigg(\Bigg\langle \sigma(u^*\beta_{u^*u^*} + v^*\beta_{v^*u^*}) + (u^*)_\phi \beta_{u^*v^*} + (v^*)_\phi \beta_{v^*v^*} + \frac{\tan\phi}{a}(u^*\beta_{v^*u^*} - v^*\beta_{u^*u^*})\Bigg\rangle\Bigg), \tag{A15}$$

$$L3(n) = -\Bigg(\Bigg\langle \sigma(u^*\beta_{\langle u\rangle u^*} + v^*\beta_{\langle v\rangle u^*}) + (u^*)_\phi \beta_{\langle u\rangle v^*} + (v^*)_\phi \beta_{\langle v\rangle v^*} + \frac{\tan\phi}{a}(u^*\beta_{\langle v\rangle u^*} - v^*\beta_{\langle u\rangle u^*})\Bigg\rangle\Bigg), \tag{A16}$$

$$L4(n) = -\Bigg(\sigma(\langle u\rangle \beta_{\langle u\rangle\langle u\rangle} + \langle v\rangle \beta_{\langle u\rangle\langle v\rangle}) + (\langle u\rangle)_\phi \beta_{\langle v\rangle\langle v\rangle} + (\langle v\rangle)_\phi \beta_{\langle v\rangle\langle v\rangle} + \frac{\tan\phi}{a}(\langle u\rangle \beta_{\langle v\rangle\langle u\rangle} - \langle v\rangle \beta_{\langle u\rangle\langle u\rangle})\Bigg). \tag{A17}$$

In $L1(n)$, wave n is transient and other interacting waves are standing and transient and hence it represents kinetic energy transfer to transient eddy of wave number n due to wave-to-wave interaction between standing and transient eddies of all other wave numbers.

In $L2(n)$, all the interacting waves are transient waves and hence represent kinetic energy transfer to transient eddy of wave number n due to wave-to-wave interaction of transient eddies of all other wave numbers.

In $L3(n)$, wave n is standing and all other interacting waves are transient and hence it represents kinetic energy transfer to standing eddy of wave number n due to wave-to-wave interaction of transient eddies of all other wave numbers.

In $L4(n)$, all the interacting waves are standing and hence represent kinetic energy transfer to standing eddy of wave number n due to wave-to-wave interaction of standing eddies of all other wave numbers.

$C1(n)$ and $C2(n)$ terms represent the conversion of eddy available potential energy to eddy kinetic energy for transient and standing wave number n respectively.

Other symbols in the above equations have the following meaning:

a	Radius of the earth.
ϕ	Latitude.
λ	Longitude.
[ ]	Zonal average.
*	Departure from time mean.
$\langle\ \rangle$	Time average.
m, n	Zonal wave numbers.

In the present study, we have truncated the series in equation (3.1) up to wave number 10 only.

It is possible to derive the following important relationships:

$$\langle K(n)\rangle = \sum_{i=1}^{i=2} Ki(n), \quad \langle J(n)\rangle = \sum_{i=1}^{i=2} Ji(n)$$

$$\langle M(n)\rangle = \sum_{i=1}^{i=4} Mi(n), \quad \langle L(n)\rangle = \sum_{i=1}^{i=4} Li(n). \tag{A18}$$

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