Role of Triad Kinetic Energy Interactions for Maintenance of Upper Tropospheric Low Frequency Waves during Summer Monsoon 1988

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ABSTRACT

In order to determine nonlinear energy exchanges into individual triad interactions in the frequency domain, spectral formulas are derived by use of the cross–spectral technique. First time attempt has been made to understand the problem of maintenance of low frequency waves for tropical weather system by using this technique. The TOGA basic level III daily wind analyses on a 2.5 degree square grid around the global zone from 20°S–30°N at 200 hPa for 92–day periods covering June, July and August of 1988 are used. Kinetic energy is gained at high frequencies and lost at low frequencies. In the planetary scale dynamics over tropics, barotropic nonlinear energy transfer plays a negative role. Low frequency wave of period 45 day loses maximum amount of energy when it interacted with frequencies of periods 92 day and 30 day. 45 day cycle is also the main source of energy for other frequencies. Distrubances of period 15 day gain maximum amount of energy. The major contribution comes from the triad interaction of the frequencies <7,1,6>. North of 20°N low frequency waves of period 30 to 92–day gain energy through nonlinear triad interaction with the maximum gain at 22.5°N. The study may help to investigate the rapid loss of predictability of low frequency modes over tropics.

Key words: Cross–spectral technique, Low frequency mode

I. INTRODUCTION

Observations have shown the presence of low frequency motions on the time scale of roughly 30 to 50 days. There are several regional and global aspects of these oscillations that have been emphasized in recent literature. Among these one observational aspect relevant to this problem is the energy exchange in the frequency domain. The maintenance of low frequency modes has to be addressed via detailed computations of energetics in the frequency domain using daily analysed data sets over global tropics covering many years. These studies are somewhat analogous to the estimates of energetics in the zonal wavenumber domain. In the frequency domain, the kinetic to kinetic energy exchanges can occur among long term mean flows and other frequencies, or among triads of frequencies.

Sheng and Hayashi (1990a, 1990b) studied the energetics in the frequency domain using two versions of the FGGE III b data set, processed at GFDL and ECMWF. They also applied the analysis of spectral energetics in the frequency domain to several observed datasets and those simulated by a GFDL general circulation model. Their results showed that in the tropics the kinetic energy is transferred from transients of longer time scales to those of shorter time scales. But over the Northern Hemisphere the direction of transfer of energy is from high frequency to low frequency wave. Yasunari (1980, 1981) emphasized the relationship between the low frequency oscillations and the Northern Hemisphere Summer monsoon. The results of energetics calculations, performed by Sheng (1986) show that the low frequency modes on the time scale of 30 to 50 days receive a substantial amount of kinetic energy from the high frequencies.

A rapid loss of predictability of low frequency modes in real data long-term integrations has been noted at ECMWF and at NMC. Once starts integrating the model, high frequency modes develop and amplify by gaining energy from the low frequency modes via the nonlinear wave-wave energy exchanges. As the high frequency modes amplify, the low frequency modes degenerate and get contaminated by the high frequency modes.

The computation of energy exchanges in the frequency domain carried out by T.N. Krishnamurti et al. (1990) for the control and the anomaly experiments in their study of predictability of low frequency modes showed that the energy exchange from the higher to the lower frequencies is very small. Observational energetics however, do imply the maintenance of low frequency modes crucially depending on this energy exchange. Ways to parameterize this energy exchange in the frequency domain require further observational studies. Interactions in frequency domain by use of the cross-spectral technique for 200 hPa during monsoon 1988 are studied in this paper. The computations are carried out to identify the dominant triad interactions and related dynamical mechanism responsible for maintenance of low frequency waves over global tropical belt. The computations are carried out to identify the preferred latitude and frequency for triad energy interactions.

II. FORMULATION

1. *Frequency Cross Spectra*

It is assumed that time series data $u(t)$ and $v(t)$ are cyclic and discrete in time. These series are represented by a time-Fourier series with discrete frequencies (n) as

$$u(t)=\sum_{n=0}^{N}(C_n^u\cos nt+S_n^u\sin nt). \tag{A}$$

In particular, $C_0^u=u_0$ (time mean) and $S_0^u=0$.

The sample frequency cospectra $P_n(u,v)$ is defined as

$$P_n(u,v)=\frac{1}{2}(C_n^u C_n^v+S_n^u S_n^v). \tag{B}$$

2. *Kinetic Energy Spectra*

The equations of motion and continuity in spherical pressure coordinate system in flux form can be written as:

$$\frac{\partial u}{\partial t}=-[\frac{\partial}{\partial x}uu+\frac{\partial}{\partial y}vu+\frac{\partial}{\partial p}wu-\frac{\tan\varphi}{a}uv]$$
$$+2\Omega\sin\varphi v-g\frac{\partial z}{\partial x}+F_u, \tag{1}$$

$$\frac{\partial v}{\partial t}=-[\frac{\partial}{\partial x}uv+\frac{\partial}{\partial y}vv+\frac{\partial}{\partial p}wv+\frac{\tan\varphi}{a}uu]$$
$$-2\Omega\sin\varphi u+\frac{g}{a}\frac{\partial z}{\partial\varphi}+F_v, \tag{2}$$

$$0 = -[\frac{RT}{p\theta}]\theta - g\frac{\partial z}{\partial p} , \tag{3}$$

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial p} , \tag{4}$$

where

$$\frac{\partial}{\partial x}(\quad) = \frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}(\quad),$$

$$\frac{\partial}{\partial y}(\quad) = \frac{1}{a}\frac{\partial}{\partial\varphi}(\quad)$$

and the other symbols have their usual meanings.

Kinetic energy per unit mass $K(n)$ for frequency n is defined by

$$K(n) = \frac{1}{2}[P_n(u,u) + P_n(v,v)], \tag{5}$$

where P_n is the frequency cospectrum.

Following Hayashi (1980) and Sheng (1986) the final form of the kinetic energy equation in the frequency domain is written as

$$0 = \langle K \cdot K(n) \rangle - P_n(W,\alpha) - g[\frac{\partial}{\partial x}P_n(U,Z) + \frac{\partial}{\partial y}P_n(V,Z) + \frac{\partial}{\partial p}P_n(W,Z)] - D(n), \tag{6}$$

where

$$\langle K \cdot K(n) \rangle = -[P_n(u,\frac{\partial}{\partial x}uu) + P_n(u,\frac{\partial}{\partial y}vu) + P_n(u,\frac{\partial}{\partial p}wu) + P_n(v,\frac{\partial}{\partial x}uv) + P_n(v,\frac{\partial}{\partial y}vv) + P_n(v,\frac{\partial}{\partial p}wv)] + \frac{\tan\varphi}{a}[P_n(u,uv) - P_n(v,uv)]$$

and $D(n) = -P_n(u,F_u) - P_n(v,F_v)$.

$\langle A(n) \cdot K(N) \rangle = P_n(W,\alpha)$ which denotes the baroclinic conversion from APE to KE at frequency n. According to Fjortoft (1953) a transfer of kinetic energy from or into a frequency n occurs when the frequencies of oscillations a, b and c are respectively n, $(n \pm m)$, and m as related by $n = (n \pm m) \mp m$.

It is important to point out at this stage that Eq. (6) corresponds to other time change of amplitude of periodic oscillation with frequency n. Therefore, according to Hayashi (1982), it indeed represents the generation, maintenance and dissipation of spectral energy.

Following Hayashi (1980), the nonlinear energy transfer spectra $\langle K \cdot K(n) \rangle$ can be further partitioned into two parts as

$$\langle K \cdot K(n) \rangle = \langle L(n) \rangle + \langle K(0) \cdot K(n) \rangle$$

Here $\langle L(n) \rangle$ is the transfer of kinetic energy into frequencies excluding 0 (time mean), while $K(0) \cdot K(n)$ is the transfer of energy into frequency n by interaction between the mean flow and frequency n.

By definition, $\langle L(n) \rangle$ is given by

$$<L(n)> = -P_n(u,\frac{\partial}{\partial x}u'u') + P_n(u,\frac{\partial}{\partial y}v'u') + P_n(u,\frac{\partial}{\partial p}w'u')$$
$$+ P_n(v,\frac{\partial}{\partial x}u'v') + P_n(v,\frac{\partial}{\partial y}v'v') + P_n(v,\frac{\partial}{\partial p}w'v')]$$
$$+\frac{\tan\varphi}{a}[P_n(u,u'v') - P_n(v,u'u')].$$

Where the prime denotes deviation from time mean for frequency spectra.
The interaction between the time–mean and the time transient motions is given by

$$<K(0)\cdot K(n)> = <K\cdot K(n)> - <L(n)>$$

3.*Explicit Expressions to Have Triad Interaction in the Frequency Domain*

The theory of harmonic analysis shows that if $X_1, X_2, ..., X_s, ..., X_r$ are equi–spaced values of any observed parameter $X = f(t)$ at the time epochs $t_1, t_2, ..., t_s, ..., t_r$, the data series can be exactly represented by a finite a series of n harmonics $f(t_s) = \sum_n (XOC_n \cos nt_s + XOS_n \sin nt_s)$, where $t_s = \frac{2\pi}{r}s$ $(s = 1,2,3,......,r)$ and $n = \frac{1}{2}(r-1)$ or $r/2$ depending upon r is odd or even. The expressions for the Fourier coefficients are

$$XOC_k = \frac{2}{r}\sum_{s=1}^{r} X_s \cos kt_s \qquad (k = 1,2,3,\cdots n)$$
$$XOS_k = \frac{2}{r}\sum_{s=1}^{r} X_s \sin kt_s$$

Similarly, any time transient field $X' = f'(t)$ can be expressed as:

$$f'(t_s) = \sum_n (XTC_n \cos nt_s + XTS_n \sin nt_s).$$

Following Chakraborty (1995), expanding all the quantities appearing in (7) followed by evaluation of the different frequency cospectra P_n we will obtain $<L(n)>$

$$=[\frac{1}{2}\left[\begin{array}{c} +\sum\limits_{r+s=n} \\ +\sum\limits_{r-s=n} \\ +\sum\limits_{r-s=-n}\end{array}\right] \begin{array}{l} UOC_n\cdot UTC_r\cdot(2\frac{\partial UTC_s}{\partial x}+\frac{\partial VTC_s}{\partial y}+\frac{\partial WTC_s}{\partial p} \\ \qquad +\frac{\tan\varphi}{a}\cdot VTC_s) \\ +UOC_n\cdot(\frac{\partial}{\partial y}UTC_r\cdot VTC_s+\frac{\partial}{\partial p}UTC_r\cdot WTC_s) \\ +VOC_n\cdot UTC_r(\frac{\partial}{\partial x}VTC_s-\frac{\tan\varphi}{a}\cdot UTC_s) \\ +VOC_n\cdot VTC_r(2\cdot\frac{\partial}{\partial y}VTC_s+\frac{\partial}{\partial p}WTC_s) \\ +VOC_n\cdot(\frac{\partial}{\partial x}UTC_r\cdot VTC_s+\frac{\partial}{\partial p}VTC_r\cdot WTC_s)\end{array}$$

$$
+\frac{1}{2}\left[\begin{array}{c} +\sum\limits_{r+s=n} \\ \\ +\sum\limits_{r-s=n} \\ \\ -\sum\limits_{r-s=-n}\end{array}\right]
\begin{array}{l}
UOS_n \cdot UTS_r\Big(2\frac{\partial UTC_s}{\partial x}+\frac{\partial}{\partial y}VTC_s+\frac{\partial}{\partial p}WTC_s \\
\qquad\qquad +\frac{\tan\varphi}{a}\cdot VTC_s\Big) \\
+UOS_n \cdot \Big(\frac{\partial}{\partial y}UTS_r \cdot VTC_s+\frac{\partial}{\partial p}UTS_r \cdot WTC_s\Big) \\
+VOS_n \cdot UTS_r\Big(\frac{\partial}{\partial x}VTC_s-\frac{\tan\varphi}{a}\cdot UTC_s\Big) \\
+VOS_n \cdot VTS_r\Big(2\cdot\frac{\partial}{\partial y}VTC_s+\frac{\partial}{\partial p}WTC_s\Big) \\
+VOS_n \cdot \Big(\frac{\partial}{\partial x}UTS_r \cdot VTC_s+\frac{\partial}{\partial p}VTS_r \cdot WTC_s\Big)
\end{array}
$$

$$
+\frac{1}{2}\left[\begin{array}{c} -\sum\limits_{r+s=n} \\ \\ +\sum\limits_{r-s=n} \\ \\ +\sum\limits_{r-s=-n}\end{array}\right]
\begin{array}{l}
UOC_n \cdot UTS_r\Big(2\frac{\partial}{\partial x}UTS_s+\frac{\partial}{\partial y}VTS_s+\frac{\partial}{\partial p}WTS_s \\
\qquad\qquad +\frac{\tan\varphi}{a}\cdot VTS_s\Big) \\
+UOC_n \cdot \Big(\frac{\partial}{\partial y}UTS_r \cdot VTS_s+\frac{\partial}{\partial p}UTS_r \cdot WTS_s\Big) \\
+VOC_n \cdot UTS_r\Big(\frac{\partial}{\partial x}VTS_s-\frac{\tan\varphi}{a}\cdot UTS_s\Big) \\
+VOC_n \cdot VTS_r\Big(2\frac{\partial}{\partial y}VTS_s+\frac{\partial}{\partial p}WTS_s\Big) \\
+VOC_n \cdot \Big(\frac{\partial}{\partial x}UTS_r \cdot VTS_s+\frac{\partial}{\partial p}VTS_r \cdot WTS_s\Big)
\end{array}
$$

$$
+\frac{1}{2}\left[\begin{array}{c} +\sum\limits_{r+s=n} \\ \\ -\sum\limits_{r-s=n} \\ \\ +\sum\limits_{r-s=-n}\end{array}\right]
\begin{array}{l}
UOS_n \cdot UTC_r\Big(2\frac{\partial}{\partial x}UTS_s+\frac{\partial}{\partial y}VTS_s+\frac{\partial}{\partial p}WTS_s \\
\qquad\qquad +\frac{\tan\varphi}{a}\cdot VTS_s\Big) \\
+UOS_n \cdot \Big(\frac{\partial}{\partial y}UTC_r \cdot VTS_s+\frac{\partial}{\partial p}UTC_r \cdot WTS_s\Big) \\
+VOS_n \cdot UTC_r\Big(\frac{\partial}{\partial x}VTS_s-\frac{\tan\varphi}{a}\cdot UTS_s\Big) \\
+VOS_n \cdot VTC_r\Big(2\frac{\partial}{\partial y}VTS_s+\frac{\partial}{\partial p}WTS_s\Big) \\
+VOS_n \cdot \Big(\frac{\partial}{\partial x}UTC_r \cdot VTS_s+\frac{\partial}{\partial p}VTC_r \cdot WTS_s\Big)\Big]
\end{array}
\qquad (C)
$$

III. DATA AND COMPUTATION

The TOGA basic level III daily wind analyses on a 2.5 degree square grid around the global zone from 20°S–30°N at 200 hPa for 92–day periods covering June, July and August of 1988 are used. Stationary (92–day average field) and transient (departure from 92–day average field) components are obtained.

The daily observed and transient wind fields are subjected to harmonic analysis. Expanding the quantities appearing in (7) followed by computation of the different frequency cospectra P_n, the nonlinear triad interaction in frequency domain is obtained from the equations (C) neglecting the baroclinic terms.

IV. RESULTS

In the present study the energy reservoirs are regrouped as motions of the time mean, 92–day cycle, low frequency, which represents approximately the frequency range between the synoptic time scale and the 92–day cycle, and high frequency, which represents the synoptic time scales shorter than 15 days. The grouping is only subjective and is meant to provide a simplified view of the energetics in the frequency domain. From the Table 1 it is seen that over the global tropics energy is gained at high frequencies and lost at low frequencies. The 15–day period is chosen because the transition frequency between the gain and loss corresponds near to this frequency. It is noticed that high frequency wave of period 4–5 day again losing energy by triad interaction. Negative energy transfers are mostly concentrated in the low frequency region of periods 45–day to 92–day. It is important to note that the situation is almost similar for spectral energetics in the wavenumber domain at 200 hPa where disturbances of low wavenumbers (long waves) lose energy by wave–wave interaction. A major portion of the loss is received by the synoptic and sub–synoptic waves and a small portion is transported away from the monsoon region (Chakraborty and Mishra, 1993). It is seen that low frequency waves lose enormous amount of energy, part of which is received by the high frequency waves and major protion is transported away from the tropical monsoon region. This is an indication that the nonlinear interaction of KE in the extratropics takes the opposite direction of that in the tropics. Sheng and Hayashi (1990), concluded that kinetic energy is lost from the high frequency band and KE is gained by the low frequency land in the extratropics, the lower latitudes show sign reversal for both frequency bands. Therefore in the planetary scale dynamics over tropics wave–wave interaction plays a negative role.

Apart from frequency 1 of 92–day period, the contributions of frequency 2 and 3 of periods 45 and 30 days are dominant in almost every energy triad interaction. In the present study the lowest frequency corresponds to 92–day period. Therefore interaction of this frequency with frequencies of periods higher than 92–day is not included. Therefore nonlinear interaction of this frequency is not complete. Frequency 2 of period 45–day loses maximum amount of energy when it interacted with frequencies of periods 92–day and 30–day. The total energy loss of 45–day oscillation is found to be maximum as compared to those of other frequencies. It is noticed that disturbance of period 15–day gains maximum amount of energy. The major contribution of this gain comes from the triad interaction of the frequencies $<7,1,6>$. The role of 92–day period for energy transfer of slow and fast transient is quite significant. The energy transfer of synoptic scale transient wave associated about with frequency 19 depends crucially on interaction of 92–day period oscillation with fast transient wave associated with frequency 20. We can say that the 45–day cycle is the main source of energy for other frequencies. It was found by Sheng and Hayashi (1990) that global average nonlinear KE is transferred in a direction opposite to that in the tropics. The magnitude of energy transfer in extra–tropics is greater than that in the tropics, therefore, the global average has the same sign as the extratropics. Therefore, barotropic nonlinear KE transfer is a secondary process for maintenance of low frequency waves over tropics. It is speculated that apart from barotropic energy conversion from time mean flow to the low frequency

Table 1(a). Decomposition of the Kientic Energy Exchange among Frequencies Due to Nonlinear Interactions into Triad Contributions for the Summer M… 1988 at 200 hPa (n = 1 to 10) in the Units of 10^{-7} wkg^{-1}

(r,s) *n*	(1,)	(2,)	(3,)	(4,)	(5,)	(6,)	(7,)	(8,)	(9,)	(10,)	(11,)	(12,)	(13,)	(14,)	(15,)	(16,)	(17,)	(18,)	(19,)	(20,)	$\sum$
		(2,1)	(3,2)	(4,3)	(5,4)	(6,5)	(7,6)	(8,7)	(9,8)	(10,9)	(11,10)	(12,11)	(13,12)	(14,13)	(15,14)	(16,15)	(17,16)	(18,17)	(19,18)	(20,19)	
1		−16	−14.1	6.3	3.1	−8.1	−1.81	2.46	−.63	4.7	2.0	−.43	.88	1.2	−1.51	.71	.94	−.18	−.02	1.95	−29
	(1,1)		(3,1)	(4,2)	(5,3)	(6,4)	(7,5)	(8,6)	(9,7)	(10,8)	(11,9)	(12,10)	(13,11)	(14,12)	(15,13)	(16,14)	(17,15)	(18,16)	(19,17)	(20,16)	
2	−14		−20	−2.85	−3.5	−1.02	−2.52	2.6	2.6	.39	−2.01	−.35	−.69	1.16	.07	−.19	1.14	.18	−.58	−.60	−40
	(1,2)			(4,1)	(5,2)	(6,3)	(7,4)	(8,5)	(9,6)	(10,7)	(11,8)	(12,9)	(13,10)	(14,11)	(15,12)	(16,13)	(17,14)	(18,15)	(19,16)	(20,11)	
3	−6.1			.57	−1.27	−1.44	−.61	.11	.12	−.48	−2.1	.24	−.82	.64	.13	1.22	.42	.08	−.39	−.03	−7.66
	(1,3)	(2,2)			(5,1)	(6,2)	(7,3)	(8,4)	(9,5)	(10,6)	(11,7)	(12,8)	(13,9)	(14,10)	(15,11)	(16,12)	(17,13)	(18,14)	(19,15)	(20,16)	
4	2.9	−1.3			−3.52	−1.92	−.34	−.32	.92	.09	−.97	−.58	1.14	−.25	.39	.95	.39	.03	.34	−.85	−2.0
	(1,4)	(2,3)				(6,1)	(7,2)	(8,3)	(9,4)	(10,5)	(11,6)	(12,7)	(13,8)	(14,9)	(15,10)	(16,11)	(17,12)	(18,13)	(19,14)	(20,15)	
5	−3.7	−.71				−2.3	.10	.59	−.33	−1.07	.31	.55	−.67	.35	−.60	−.03	.23	−.15	.16	−.35	−6.2
	(1,5)	(2,4)	(3,3)				(7,1)	(8,2)	(9,3)	(10,4)	(11,5)	(12,6)	(13,7)	(14,8)	(15,9)	(16,10)	(17,11)	(18,12)	(19,13)	(20,14)	
6	4.3	−.64	1.5				5.7	−.92	.86	.99	−.31	.09	.68	.57	.03	.46	−.29	−.16	−.24	−.78	13
	(1,6)	(2,5)	(3,4)					(8,1)	(9,2)	(10,3)	(11,4)	(12,5)	(13,6)	(14,7)	(15,8)	(16,9)	(17,10)	(18,11)	(19,12)	(20,13)	
7	2.9	.33	.24					−3.11	−.12	.61	.29	−.59	−.13	.53	.21	−.07	−.1	.37	−.39	.31	.51
	(1,7)	(2,6)	(3,5)	(4,4)					(9,1)	(10,2)	(11,3)	(12,4)	(13,5)	(14,6)	(15,7)	(16,8)	(17,9)	(18,10)	(19,11)	(20,12)	
8	−.95	.87	.20	−.58					−.67	1.36	−.49	.08	−.59	.47	.36	.27	.41	−.1	−.32	.31	.59
	(1,8)	(2,7)	(3,6)	(4,5)						(10,1)	(11,2)	(12,3)	(13,4)	(14,5)	(15,6)	(16,7)	(17,8)	(18,9)	(19,10)	(20,11)	
9	0.32	−.07	.51	−.05						2.06	.07	.13	−.19	.17	.23	.14	.01	.03	−.05	.04	3.3
	(1,9)	(2,8)	(3,7)	(4,6)	(5,5)						(11,1)	(12,2)	(13,3)	(14,4)	(15,5)	(16,6)	(17,7)	(18,8)	(19,9)	(20,10)	
10	−1.3	.21	−.30	.11	0.00						1.32	.08	.23	−.01	.16	.46	−.02	.03	.1	.20	1.5

Table 1(b). Decomposition of the Kinetic Energy Exchange among Frequencies Due to Nonlinear Interactions into [illegible] Contributions for the Summer Monsoon, 1988 at 200 hPa ($n = 11$ to 20) in the Units of 10^{-7} wkg^{-1}

(r,s) n	(1,)	(2,)	(3,)	(4,)	(5,)	(6,)	(7,)	(8,)	(9,)	(10,)	(11,)	(12,)	(13,)	(14,)	(15,)	(16,)	(17,)	(18,)	(19,)	(20,)	Σ
	(1,10)	(2,9)	(3,8)	(4,7)	(5,6)							(12,1)	(13,2)	(14,3)	(15,4)	(16,5)	(17,6)	(18,7)	(19,8)	(20,9)	
11	−.28	−.61	.36	.23	.39							.73	−.08	.51	−.32	.11	.20	.10	−.33	−.24	.07
	(1,11)	(2,10)	(3,9)	(4,8)	(5,7)	(6,6)							(13,1)	(14,2)	(15,3)	(16,4)	(17,5)	(18,6)	(19,7)	(20,8)	
12	2.3	−.64	−.11	−.44	−.31	.24							.13	.37	.15	.62	−.22	.08	−.28	−.28	.57
	(1,12)	(2,11)	(3,10)	(4,9)	(5,8)	(6,7)								(14,1)	(15,2)	(16,3)	(17,4)	(18,5)	(19,6)	(20,7)	
13	−1.6	1.0	−.67	−.53	.40	.28								.75	−.32	.16	.45	.25	−.56	.77	.34
	(1,13)	(2,12)	(3,11)	(4,10)	(5,9)	(6,8)	(7,7)								(15,1)	(16,2)	(17,3)	(18,4)	(19,5)	(20,6)	
14	−.63	−.22	.22	.10	−.1	.04	−.1								.26	−.07	−0.03	.08	.16	0.0	.44
	(1,14)	(2,13)	(3,12)	(4,11)	(5,10)	(6,9)	(7,8)									(16,1)	(17,2)	(18,3)	(19,4)	(20,5)	
15	−.04	−.07	−.07	.06	0.0	.06	.11									−.17	−.02	.06	−.04	.08	.13
	(1,15)	(2,14)	(3,13)	(4,12)	(5,11)	(6,10)	(7,9)	(8,8)									(17,1)	(18,2)	(19,3)	(20,4)	
16	−.06	−.09	−.02	−.13	−.06	−.18	.21	−.04									.35	.22	.02	−.40	.63
	(1,16)	(2,15)	(3,14)	(4,13)	(5,12)	(6,11)	(7,10)	(8,9)										(18,1)	(19,2)	(20,3)	
17	.99	.07	−.12	−.01	−.11	0.0	−.59	−.04										1.03	−.07	.14	.55
	(1,17)	(2,16)	(3,15)	(4,14)	(5,13)	(6,12)	(7,11)	(8,10)	(9,9)										(10,1)	(20,2)	
18	.11	.05	.03	−.06	.03	−.01	−.18	.01	−.04										−.47	−.60	−1.6
	(1,18)	(2,17)	(3,16)	(4,15)	(5,14)	(6,13)	(7,12)	(8,11)	(9,10)											(20,1)	
19	−.49	−.06	.08	−.07	−.02	.11	.04	.08	−.02											−1.72	−1.6
	(1,19)	(2,18)	(3,17)	(4,16)	(5,15)	(6,14)	(7,13)	(8,12)	(9,11)	(10,10)										—	
20	−.49	−.25	−.14	−.13	.02	.04	.15	−.06	.04	.07											−1.5

transients, the boundary term, generation or the conversion term may be important for maintenance of low frequency waves in the tropics. Here in the last column of the Table 1, $\sum$ stands for contributions from all possible triad interactions including frequency 46 of period 2 day. Although the calculations were done with a truncation at 46 frequencies, only the first 20 frequencies are displayed in Table 1.

Fig. 1(a) and (b) show the latitude frequency distribution of nonlinear kinetic energy transfer. It is noticed that north of 20°N low frequency waves of period 30 to 92 days gain energy with the maximum gain at about 22.5°N which is the mean latitude of movement of tropical depression (Mishra et al., 1983). This is in agreement with the findings of Sheng and Hayashi (1990) who showed that nonlinear interaction of KE takes place in the opposite direction of that in the extratropics. They considered the extratropics are the area north of 20.625°N. The transport of energy by nonlinear interaction away from the region south of 20°N accounts for the latitudinally averaged energy loss of low frequency waves over 20°S–30°N. Table 2 is presented to support this statement. The positive energy transfer of low frequency spread of transfer of KE by nonlinear interaction of high frequency waves is almost over the whole latitudinal belt. Since the high frequency motions were not filtered out from the analysed data, they would contribute to a contamination of low frequency modes from nonlinear energy exchanges. As we found the contributions of frequency 2 and 3 of periods 45 and 30 days are dominant in almost every energy triad interaction, it is very much essential that the very large scale quasi–stationary waves and their fluctuations in the tropics are to be satisfactorily simulated by different global models to improve the predictability in the tropics for the very large scales namely zonal wavenumbers 1–3.

Table 2. *Latitude–Frequency Distribution of Nonlinear Kinetic Energy Transfer in Units of* 10^{-7}**wkg**$^{-1}$

Lat.	25°N	22.5°N	20°N	17.5°N	15°N	12.5°N	10°N	7.5°N	5°N	2.5°N	EQ.
Freq. No.											
1	110	130	77	20	−26	−53	−37	−18	−13	−3.7	1.5
2	62	89	68	41	12	3.0	−7.4	−6.6	−13	−11	−3.7
3	31	19	5.2	−4.7	−6.6	−8.4	−7.9	−3.6	.70	−1.7	−.12
4	20	11	11	4.5	−3.2	−1.9	−1.7	−.40	.01	−1.9	.41
5	−16	−9.3	4.3	.95	−1.8	1.1	3.2	3.7	1.1	−2.1	−2.6
6	8.1	4.1	−7.8	−9.5	−8.2	3.9	4.2	.64	1.7	2.4	1.3
7	−2.7	−3.5	−5.1	−1.6	4.0	5.1	−.26	.94	1.2	−.36	−.91
8	2.6	4.5	4.1	4.8	5.9	1.6	−.40	.26	1.3	.13	−1.0
9	−.74	3.3	.68	4.7	1.7	−3.3	−1.0	.94	1.3	1.6	1.4
10	−.97	.19	4.6	6.6	1.8	7.0	3.1	.50	1.2	1.2	.32
11	10	7.5	−.41	2.6	1.3	2.9	1.7	.30	.93	1.2	1.1
12	2.3	1.1	5.5	2.8	−2.2	−4.1	2.4	−1.2	−3.8	−4.7	.25
13	8.5	7.5	3.2	−.20	−1.6	.20	−1.0	−0.08	−1.7	.47	2.7
14	4.6	−1.6	−.35	.12	.50	.42	2.5	3.7	1.7	−.16	.33
15	1.6	−.10	.40	.35	.90	1.3	.05	.87	.19	1.5	−1.2
16	−.10	−.89	−1.0	.51	4.6	.52	−.71	−.11	1.4	1.3	−1.1
17	1.4	1.2	.70	−.65	3.4	4.0	.62	−.61	.57	−.21	−.68
18	2.7	4.9	−.41	−.03	−.38	−2.2	1.3	.10	−.53	.68	.65
19	4.1	1.6	−2.7	−.67	−2.5	−2.4	−.64	−.06	−.16	−.44	.14
20	.76	.97	.66	.96	−1.4	−2.0	−.49	−.34	.52	−.60	.39

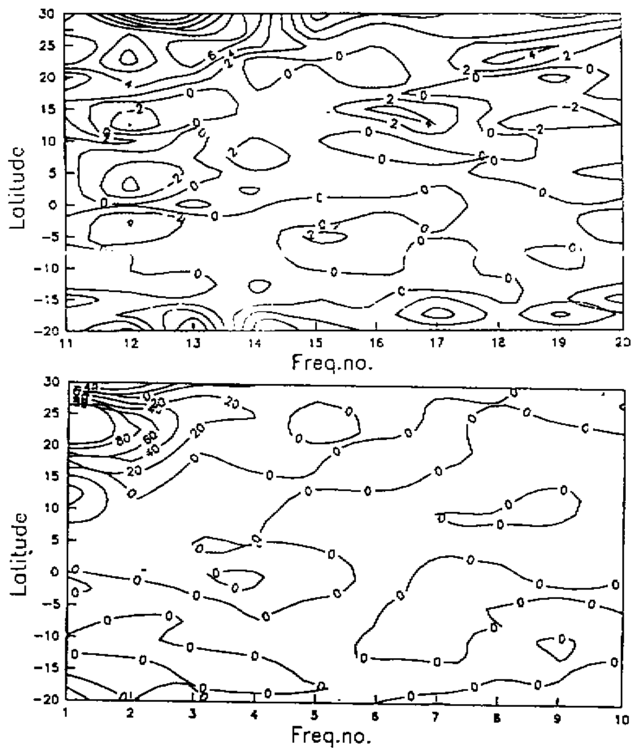

Fig. 1. A latitude–frequency plot of nonlinear kinetic energy interaction for summer monsoon, 1988 over tropics (20°S–30°N). The contours are labelled in units of $10^{-7}wkg^{-1}$.

V. SUMMARY AND CONCLUSIONS

The TOGA basic level III daily wind analysed on a 2.5° square grid around global tropical zone from 20°S–30°N at 200 hPa for June, July and August of 1988 were used to calculate the nonlinear kinetic energy exchanges into individual triad interactions in the frequency domain by use of the cross–spectral technique. The energy transfer mechanism and the dominant triad interactions responsible for maintenance of low frequency waves are identified. The preferred latitude for nonlinear energy transfer of low frequency waves is also identified.

The results of the present study show that the energy is gained at high frequencies and lost at low frequencies. It is seen that low frequency waves of period 45 day to 92 day lose enormous amount of energy, part of which is received by high frequency waves and major portion is transported away from the tropical monsoon region. Therefore our results indicate that the non–linear interaction of kinetic energy in the extratropics takes the opposite direction of that in the tropics. We can conclude from our results that in the planetary scale dynamics over tropics, barotropic nonlinear energy transfer plays a negative role. It is also found that low frequency wave of period 45 day loses maximum amount of energy when it interacted with frequencies of periods 92 day and 30 day and this 45–day cycle is the main source of energy for other frequencies. It is further seen that disturbance of period 15 day gain maximum amount of energy. The major contribution comes from the triad interaction of the frequencies <7,1,6>. Latitude–frequency distribution of nonlinear kinetic energy transfer shows that north of 20°N low frequency waves of period 30 to 92 day gain energy with the maximum gain at 22.5°N. The negative energy transfer over the region south of 20°N accounts for the loss of energy of low frequency waves over the latitudinal belt 20°S–30°N. Our results also show that the contributions of frequency 2 and 3 of periods 45 and 30 days play dominant role in almost every energy triad interaction, therefore it is very much essential that the very large scale quasi–stationary waves and their fluctuations in the tropics are to be satisfactorily simulated by different global models. Predictability in the tropics even for the very large scales namely zonal wavenumers 1–3 is about 2 days which is comparable to that for total field (Kanamitsu, 1985). This indicates that error in the very large scale dominates. The present study may help to investigate the rapid loss of predictability of low frequency modes over tropics.

Although the calculations with present data sets have provided results consistent with earlier studies, we believe that until they are confirmed by the use of more accurate datasets the results must be considered tentative. Since the high frequency motions were not filtered out from the analysed data, they could contribute to a contamination of low frequency modes from nonlinear energy exchanges. The results presented are, if not quantitative, only semi qualitative. There is considerable room for further research in this area. It is proposed to investigate the energetics in the frequency domain in the following areas:

(1) Nonlinear triad interactions with emphasis on the contrast between the extratropics and the tropics.

(2) Interseasonal variability of nonlinear triad interactions over tropics.

(3) Intercomparison between barotropic and baroclinic mechanism for maintenance of low frequency waves during summer monsoon over global tropics.

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