J. Ind. Geophys. Union (2003)
Vol.7, No.1, pp.15-24

Nonlinear Triad and Inscale processes in Madden-Julian Oscillations during summer monsoon

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ABSTRACT

The nonlinear triad interactive relationship between high and low frequency transients and time mean flow over tropics and extra tropics has been examined by use of the cross spectral technique with 3 years of European Center for Medium Range Weather Forecasts (ECMWF) 850 hpa and 200 hpa summertime wind fields, vertical velocity and temperature data. In the extratropics, at the upper troposphere, low frequency waves of period 45 days shows an overall gain of energy from its triad interactions with all other pairs of waves, particularly in the regions (20°N - 30°N and 50°N - 60°N). High frequency waves show an overall loss in this regard as well as through baroclinic in scale energy transfer. The lower latitudes consistantly show sign reversals for both frequency bands. The nonlinear interaction of KE associated with low frequency motions in the tropics takes the opposite direction of that in the extra tropics. Tropical convection plays an important role for the maintenance of tropical intraseasonal oscillations. Low frequency oscillation of 30 days period is found to be very much interactive in the planetary scale dynamics of monsoon in the upper troposphere. The results suggest that wave-CISK process and strong gradient of SST are the possible mechanisms associated with low frequency waves in the lower troposphere over the west Pacific and east coast of Africa.

INTRODUCTION

Low frequency motions in the atmosphere have attracted special attention of the meteorological community in recent years. The term "low frequency " is used here to distinguish this class of disturbances from the synoptic systems of relatively high frequency (periods 1 to 10 days) and from those of annual or interannual time scales. Observations during the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) year and subsequent to that for a recent 8-year period have clearly shown the presence of low frequency motions on time scale of roughly 30 to 50 days (Krishnamurti et. al. 1992). Madden & Julian (1971,1972), dealing with the equatorial sea level pressure field and zonal wind clearly demonstrated a dominant mode of a 40-50 days period. Yasunari (1980,1981) emphasized the relationship between the low frequency oscillations and northern Hemisphere summer monsoon. From different earlier studies it has become clear that atmospheric waves with periods longer than 10 days have different characteristics compared to their high frequency counterparts. Hayashi & Golder (1986,1988) conducted space time spectrum and filter analyses to study the propagation and structure of the tropical intraseasonal oscillations appearing in Geophysical Fluid Dynamics Laboratory (GFDL) spectral general circulation models and those found in the GFDL FGGE four-dimensional assimilation data set. The results exhibited wavenumber 1 spectral peak in the equatorial zonal velocity at eastward moving periods of 40-50 and 25-30 days. Sheng & Hayashi (1990a, b) studied the energetics in the frequency domain using two versions of the FGGE IIIb data sets processed at GFDL and ECMWF. The results discussed in their studies, though hemispherically integrated, are essentially representative of the extratropics, since the intensity of transient activity is weaker in the tropics than in the middle latitudes. Studies of energetics (Kanamitsu, Krishnamurti & Depradine 1972) indicate that energy balance in the tropics may be quite different from the extratropical regions. Although Plumb (1983) and Hayashi (1987) discussed the limitations of energetics in interpreting the dynamics of atmospheric motions, there is still enough interest to contrast the energetics of the tropics with that of the extratropics.

In order to understand the physical mechanism for maintenance of low frequency waves, computations of nonlinear kinetic energy (KE) exchanges into individual triad interactions in frequency domain by use of cross-spectral technique over global tropics were carried out by Chakraborty & Agarwal (1996, 1997).

A rapid loss of predictability of low frequency modes in real data long-term integrations has been noted at ECMWF and at National Meteorological Center (NMC). Once the model starts integrating 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 become contaminated by the high frequency modes.

The computations of energy exchanges in the frequency domain carried out by Krishnamurti et al. (1990) for the control and the anomaly experiments in their study of predictability of low frequency modes showed that the energy exchanges from the higher to the lower frequencies are small. Observational energetics however, do imply that the maintenance of low frequency modes crucially depends on this energy exchange. Ways to parameterizing this energy exchange in the frequency domain requires further observational studies.

The present study attempts to investigate the roles played by the transient eddies of different temporal scales through nonlinear triad interactions by use of the cross-spectral technique at 850 hPa and 200 hPa over tropics and extra tropics. We aim to increase our understanding of the relationship between high and low frequency transients and time mean flow. Further we present an energetics analysis for the summer circulations in tropics and mid-latitudes to gain insight into the underlying interactive dynamics among the low and high frequency transients and the time mean flow. The latitude frequency and longitude frequency distributions of nonlinear energy transfer over tropics and extra tropics are also computed and discussed.

FORMULATION

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 series of n harmonics

$$f(t_s) = \sum (XOC_n \cos nt_s + XOS_n \sin nt_s),$$

where $t_s = 2\pi s/r$ (s = 1,2,3,...,r) and n = (r-1)/2 or r/2 depending upon r is odd or even. The expressions for the Fourier coefficients are

$$XOC_k = \frac{2}{r}\sum_{s=1}^{r} X_s \cos kt_s$$

$$XOS_k = \frac{2}{r}\sum_{s=1}^{r} X_s \sin kt_s$$

$(k = 1,2,3,............)$

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 Hayashi (1980), the nonlinear KE triad interactions in the frequency domain < L(n) > is given by

$$\langle L(n)\rangle = \left[-P_n(U,\frac{\delta}{\delta x}U'U') + P_n(U,\frac{\delta}{\delta y}V'U') + P_n(U,\frac{\delta}{\delta p}W'U') + P_n(V,\frac{\delta}{\delta x}U'V')\right]$$
$$+\left[P_n(V,\frac{\delta}{\delta y}V'V') + P_n(V,\frac{\delta}{\delta p}W'V') + \frac{\tan\phi}{a}[P_n(U,V'V') - P_n(V,U'U')]\right] \quad ....(A)$$

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

⟨ L(n) ⟩ =

$$\frac{1}{2}\left\{+\sum_{r+s=n} + \sum_{r-s=n} + \sum_{r-s=-n}\right\}\begin{bmatrix} UOC_n.UTC_r.(2\frac{\partial}{\partial x}UTC_s + \frac{\partial}{\partial y}VTC_s + \frac{\partial}{\partial p}WTC_s + \frac{\tan\phi}{a}.VTC_s) \\ +UOC_n.(\frac{\partial}{\partial y}UTC_r.VTC_s + \frac{\partial}{\partial p}UTC_r.WTC_s) \\ +VOC_n.UTC_r(\frac{\partial}{\partial x}VTC_s - \frac{\tan\phi}{a}.UTC_s) \\ +VOC_n.VTC_r(2.\frac{\partial}{\partial y}VTC_s + \frac{\partial}{\partial p}WTC_s) \\ +VOC_n.(\frac{\partial}{\partial x}UTC_r.VTC_s + \frac{\partial}{\partial p}VTC_r.WTC_s) \end{bmatrix}$$

$$+\frac{1}{2}\left\{-\sum_{r+s=n} + \sum_{r-s=n} + \sum_{r-s=-n}\right\}\begin{bmatrix} UOC_n.UTS_r(2\frac{\partial}{\partial x}UTS_s + \frac{\partial}{\partial y}VTS_s + \frac{\partial}{\partial p}WTS_s + \frac{\tan\phi}{a}.VTS_s) \\ +UOC_n(\frac{\partial}{\partial y}UTS_r.VTS_s + \frac{\partial}{\partial p}UTS_r.WTS_s) + VOC_n.UTS_r \\ (\frac{\partial}{\partial x}VTS_s - \frac{\tan\phi}{a}.UTS_s) + VOC_n.VTS_r(2.\frac{\partial}{\partial y}VTS_s + \frac{\partial}{\partial p}WTS_s) \\ +VOC_n.(\frac{\partial}{\partial x}UTS_r.VTS_s + \frac{\partial}{\partial p}VTS_r.WTS_s) \end{bmatrix}$$

$$+\frac{1}{2}\left\{+\sum_{r+s=n} + \sum_{r-s=n} - \sum_{r-s=-n}\right\}\begin{bmatrix} UOS_n.UTS_r(2.\frac{\partial}{\partial x}UTC_s + \frac{\partial}{\partial y}VTC_s + \frac{\partial}{\partial p}WTC_s + \frac{\tan\phi}{a}.VTC_s) \\ +UOS_n(\frac{\partial}{\partial y}UTS_r.VTC_s + \frac{\partial}{\partial p}UTS_r.WTC_s) \\ +VOS_n.UTS_r(\frac{\partial}{\partial x}VTC_s - \frac{\tan\phi}{a}.UTC_s) \\ +VOS_n.(\frac{\partial}{\partial x}UTS_r.VTC_s + \frac{\partial}{\partial p}VTS_r.WTC_s) \\ +VOS_n.VTS_r(2\frac{\partial}{\partial y}VTC_s + \frac{\partial}{\partial p}WTC_s) \end{bmatrix}$$

$$+\frac{1}{2}\left\{+\sum_{r+s=n} - \sum_{r-s=n} + \sum_{r-s=-n}\right\}\begin{bmatrix} UOS_n.UTC_r(2\frac{\partial}{\partial x}UTS_s + \frac{\partial}{\partial y}VTS_s + \frac{\partial}{\partial p}WTS_s + \frac{\tan\phi}{a}.VTS_s) \\ +UOS_n.(\frac{\partial}{\partial y}UTC_r.VTS_s + \frac{\partial}{\partial p}UTC_r.WTS_s) + VOS_n.UTC_r \\ (\frac{\partial}{\partial x}VTS_s - \frac{\tan\phi}{a}.UTS_s) + VOS_n.VTC_r(2.\frac{\partial}{\partial y}VTS_s + \frac{\partial}{\partial p}WTS_s) \\ +VOS_n.(\frac{\partial}{\partial x}UTC_r.VTS_s + \frac{\partial}{\partial p}VTC_r.WTS_s) \end{bmatrix}$$

.... (B)

$$\langle A(n).K(n)\rangle = -P_n(W,\alpha) \quad .... (C)$$

is the baloclinic conversion from available potential energy (APE) to KE at frequency fn. U, V, W are the zonal, meridional and vertical velocity of wind, respectively, α is the specific volume.

Following Hayashi (1980), the nonlinear energy transfer K.K(n) can be further partitioned into two parts as

$$\langle K.K(n)\rangle = \langle L(n)\rangle + \langle K(0).K(n)\rangle \quad ....(D)$$

where $\langle K(0).K(n)\rangle$ is the transfer of energy into frequency n by interaction between the mean flow and frequency n.

DATA AND COMPUTATION

We have used the ECMWF grid point analysis data at 2.5 degree resolution. For our purpose, we extracted u, v, w and temperature fields at 850 hPa and 200 hPa for the summer months (June, July, August) of 1994, 1995 and 1996. These data sets are further divided into tropical (20°S – 20°N) and extratropical (20°N – 60°N) regions. An average over respective months for these years have been performed for the present study. To separate the high frequency transient, the low frequency eddies and the time mean flow from the total 850 hPa and 200 hPa wind field, vertical velocity and temperature fields, a temporal Fourier decomposition is used. The nonlinear triad interactions in frequency domain are obtained by computation of different frequency cospectra from the equations (B). The baroclinic inscale conversion from APE to KE and the KE interaction between time transient and time mean flows are computed from equations (C) and (D) respectively.

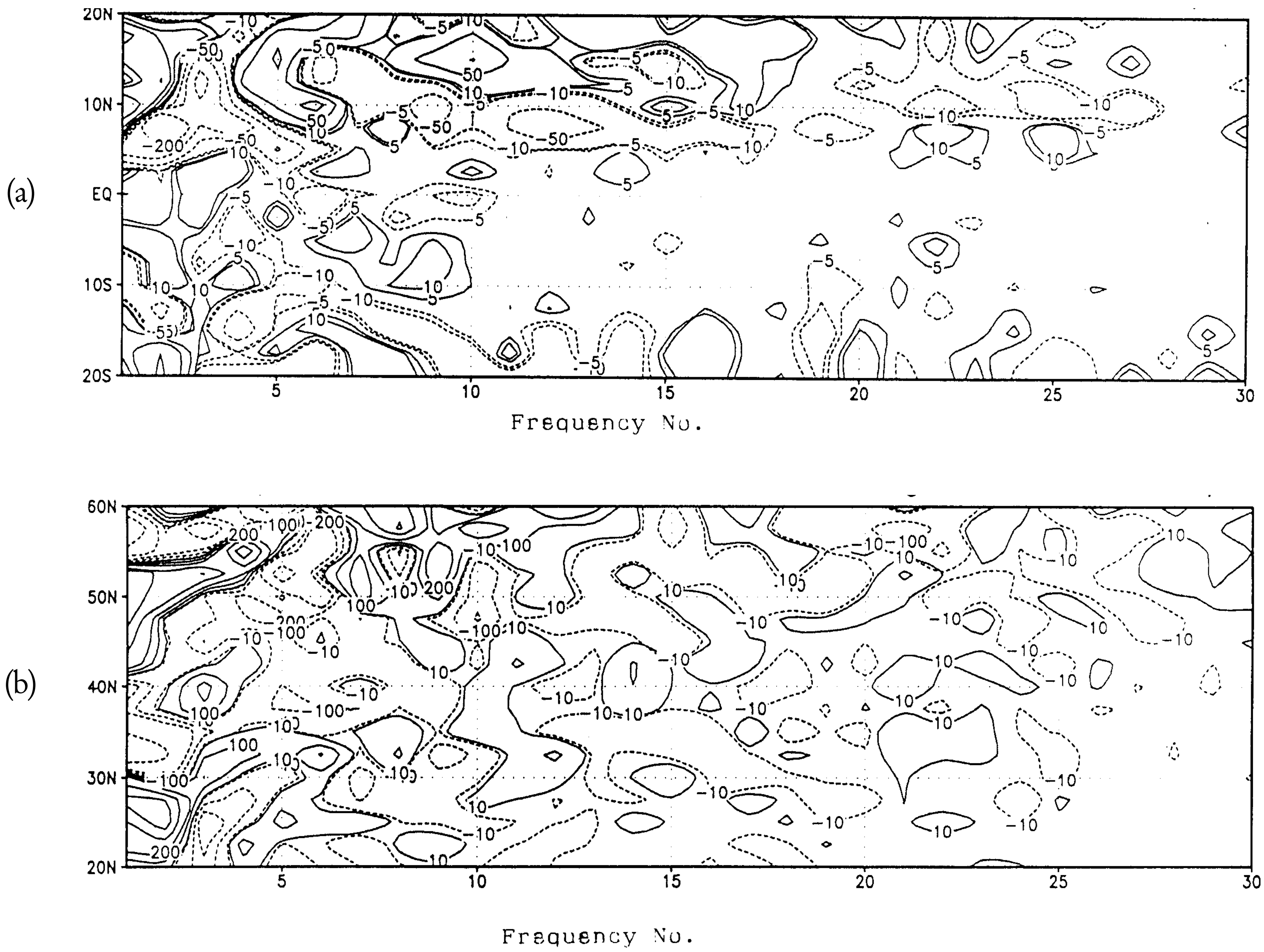

Figure1. A latitude-frequency plot of nonlinear barotropic kinetic energy exchange for the summer monsoon 1994-1996 at 850 hPa over the (a) tropics (20°S- 30°N) and (b) extra tropics (20°N-60°N). The contours are labelled in units of 10^{-6} W kg^{-1}.

(a)

(b)

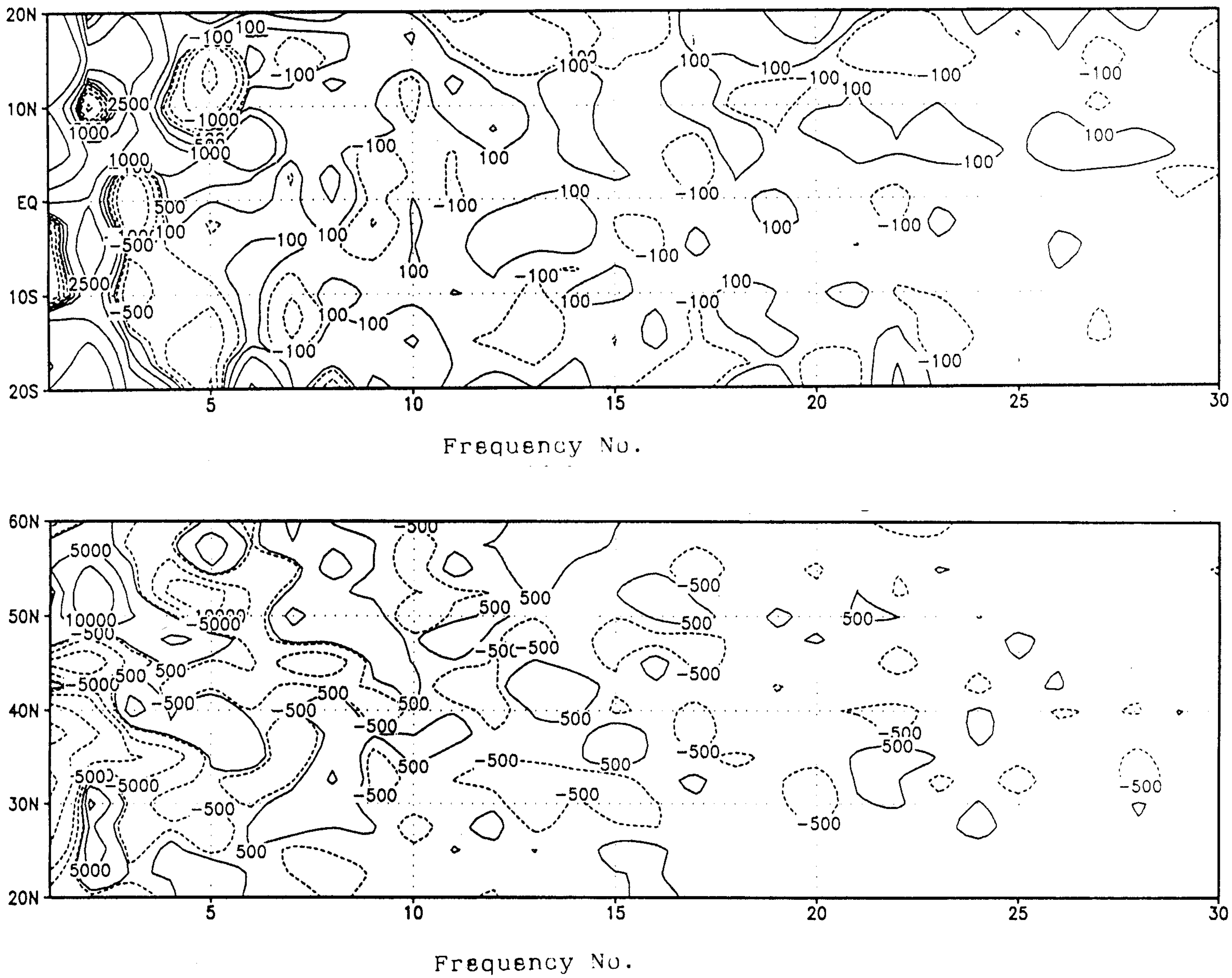

Figure 2. A latitude-frequency plot of nonlinear barotropic kinetic energy exchange for the summer monsoon 1994-1996 at 200 hPa over the (a) tropics (20°S-20°N) and (b) extra tropics (20°N-60°N). The contours are labelled in units of 10^{-6} W Kg^{-1}.

RESULTS

The distributions of the energy transformations as functions of latitude and frequency are given in Figs 1(a,b) and 2(a,b). The parameters have been integrated over relatively wide spectral frequency bands (from 2 days to 45 days) to represent high and the low frequency transients. For both computations are carried out at 200 hPa and 850 hPa as these levels are considered as the representative levels for upper and lower tropospheres, respectively. For all frequency bands the contributions are mostly from the upper troposphere in the middle latitudes. In the extra tropics at the upper troposphere low frequency waves of period 45 days show an overall gain of energy from its triad interactions with other pairs of waves particularly in the regions (20°S – 30°N & 50°N – 60°N). High frequency waves show an overall loss in this regard as well as through baroclinic inscale energy transfer [Figs 3(a) and 3(b)]. Low frequency waves loose enormous amount of energy in the tropics through barotropic energy transfer process. Though upper tropospheric waves of 30-45 period gain energy through baroclinic in scale transformation process [Figs 4(a) and 4(b)] in the tropics but loss of energy through barotropic process is much more than this gain. Overall over the tropics low frequency waves loose energy whereas high frequency waves gain energy mainly through barotropic process. The lower latitudes consistantly show sign reversals for both frequency bands. Sheng & Hayashi's (1990 a, b), Chakraborty & Agarwal's (1996,1997) works support our result. This is an indication that the nonlinear interaction of KE in the tropics takes the opposite direction of that in the extratropics. It is interesting to note that a similar observation was made in the wavenumber domain by Kanamitsu, Krishnamurti & Depradine (1972) and Chakraborty & Mishra (1993, 1997). Saltzman (1970) reviewed the energetics in the zonal wavenumber domain and concluded that both the short waves and planetary waves gain KE from the intermediate disturbances. In the tropics, however, zonal wave number 1 appears to be a major energy source, supplying KE to all other wavenumbers (Kanamitsu, Krishnamurti & Depradine 1972).

To address the difference in energy cycle between barotropic and baroclinic mechanisms over the tropics and the extratropics, estimates are made by taking integrations over these two parts of the atmosphere for barotropic and baroclinic (only conversion) processes separately. Since the present study is not concerned with a complete energy balance for these open domains, the energy flux term F(n), the APE generation G(n), and the KE dissipation D(n) are not included in the analysis to simplify the discussion. The dominant process to maintain the low frequency transients seems to be the baroclinic conversion term, $\langle A(n).K(n) \rangle$ as discussed in Krishnamurti et al. (1985).

The research work on tropical intraseasonal oscillations gained momentum after the availability of FGGE data sets. Lot of work have been done on the structure characteristics and the mechanism responsible for generating and maintaining the oscillation (e.g., Murakami & Nakazawa 1985; Hayashi & Sumi 1986; Chen 1987). Though low frequency mode is a global scale phenomenon (wavenumber 1 in zonal), it is frequently related to some regional convection regimes, such as convective activities in the equatorial western Pacific. The concept of CISK (Conditional Instability of the Second Kind) is generally invoked to parameterize the diabatic heating generated by cumulus convection in theoretical and modelling studies. (Lau & Peng, 1987; Chang & Lim 1988; Lau, Kang & Sheu 1989). It is noted from the results that, unlike in the extratropics, nonlinear interactions take away KE from the slow transients and the baroclinic conversion is the unique energy source for the low frequency KE (Fig.4(b)). Therefore, it is concluded that tropical convection plays an important role for the maintenance of tropical intraseasonal oscillations. This is consistent with Knutson & Weickmann's (1987) results, which demonstrate that the vertical structure of the 30 to 60 days oscillations is baroclinic in the tropics but equivalent barotropic poleward of about 20°N.

At 850 hPa low frequency oscillations of period (30-45) days are loosing energy to the time mean flow more or less at the same rate ($.18 \times 10^{-7}$ W kg^{-1}) over tropics and extra-tropics whereas the high frequency waves gain small amount of energy. At 200 hPa also low frequency waves transfer energy to the time mean flow over tropics however over the extratropics, the energy is transferred in the opposite direction; i.e., the flow is barotropically unstable to the low frequency disturbances. This result is in agreement with that of Wallace & Lau (1985). The role of time mean flow on the low frequency transients is found to be secondary, compared to the effect of the leading term due to nonlinear interactions in the upper and lower tropospheres. Low frequency waves suffer a net loss of energy in the troposphere over the tropics. Chakraborty & Agarwal (1996, 1997) found that low frequency waves suffer a net loss of energy in the upper troposphere.

Apart from frequency 2 of a 45 day period, the contribution of frequency 3 of 30 day period is very dominating in most energy triad interactions for maintenance of low frequency waves over extratropics and at the upper troposphere. It is also noticed that disturbance of period 15 day too gains substantial amount of energy. The major contribution of this gain comes from the triad interaction of the frequencies $\langle 6,9,3 \rangle$ where the frequency no. 3 is also involved. Thus the role of 30 day oscillation is very much important in the upper tropospheric dynamics over the extratropics. Even in the lower troposphere low frequency oscillation of 30 day period is very much interactive as compared to other oscillations but interaction is little weak as compared to that in the upper troposphere. The kinetic energy exchanges among different frequencies and the interactions between transient eddies and time mean flow are an order of magnitude smaller in the lower troposphere than in the upper troposphere over the extratropics. Chakraborty & Agarwal (1997) noticed the same over tropics also. Longitude-frequency distributions of nonlinear baroclinic KE conversion during summer at 850 hPa over tropics and extra-tropics [Figs.5(a) and 5(b)] show that

(a)

(b)

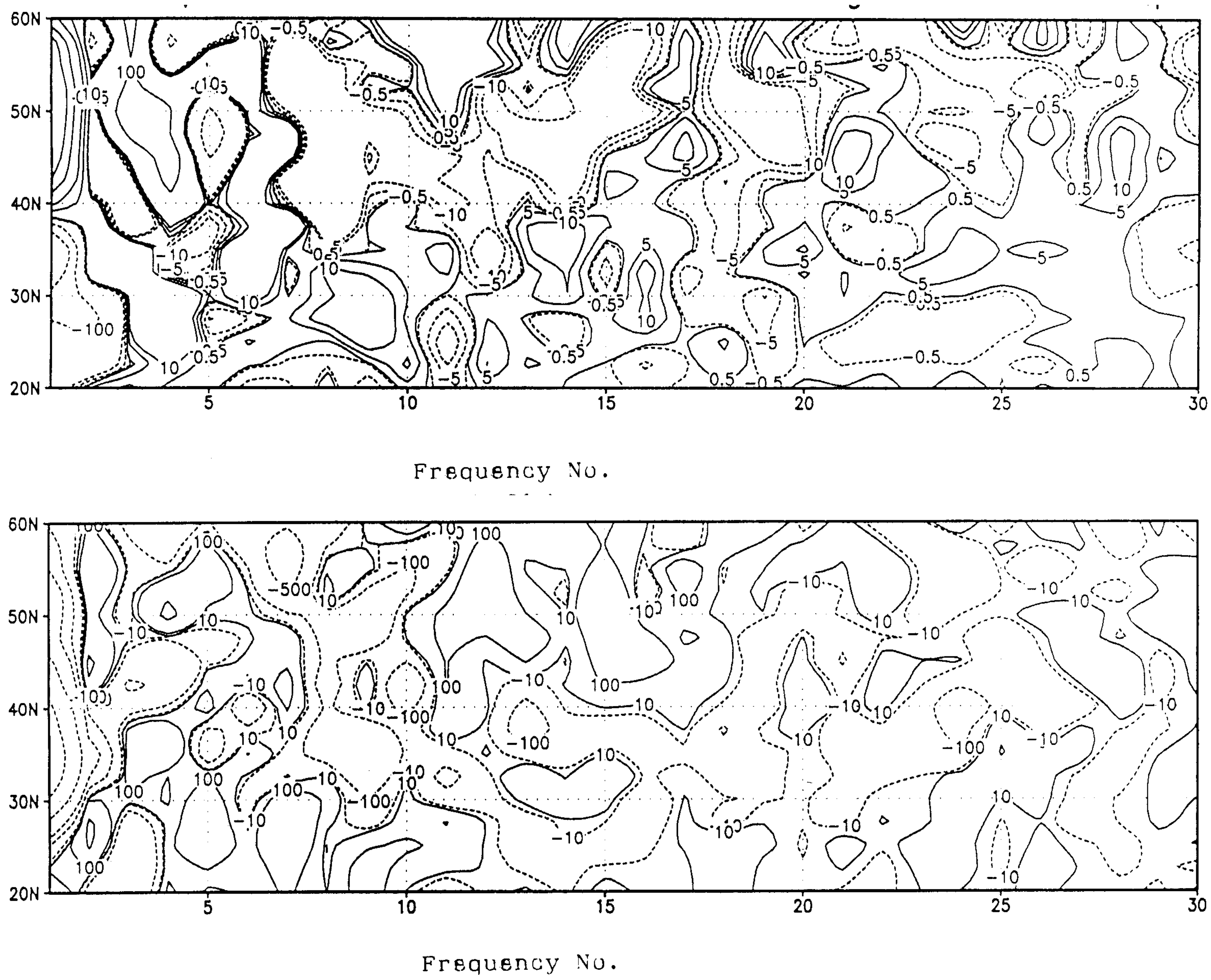

Figure 3. A latitude-frequency plot of baroclinic conversion from APE to KE for the summer monsoon 1994-1996 over the extratropics at (a) 850 hPa and (b) 200 hPa. The contours are labelled in units of 10^{-6} W Kg^{-1}

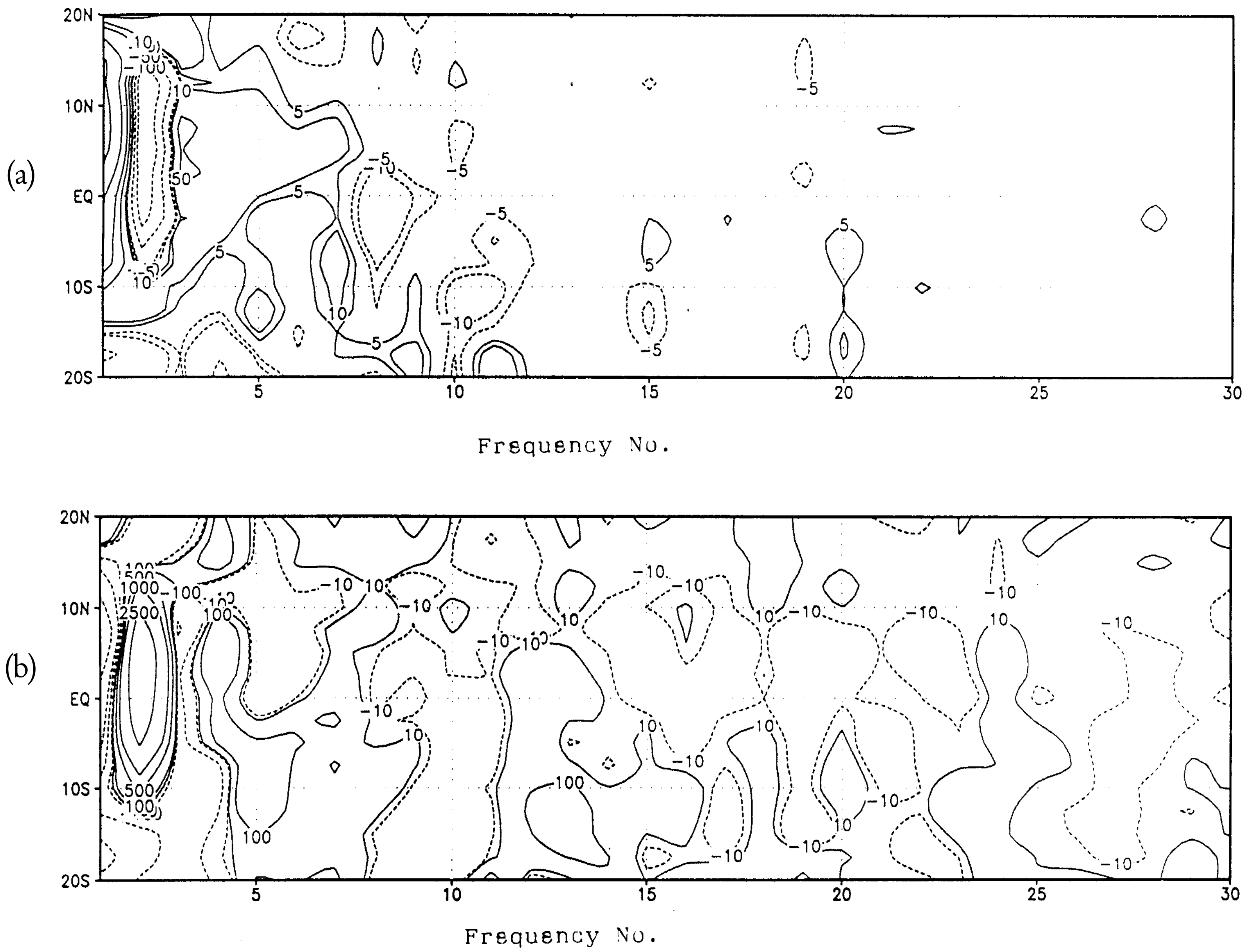

Figure 4. A latitude-frequency plot of baroclinic conversion from APE to KE for the summer monsoon 1994-1996 over the tropics at (a) 850 hPa and (b) 200 hPa. The contours are labelled in units of 10^{-6} W kg^{-1}

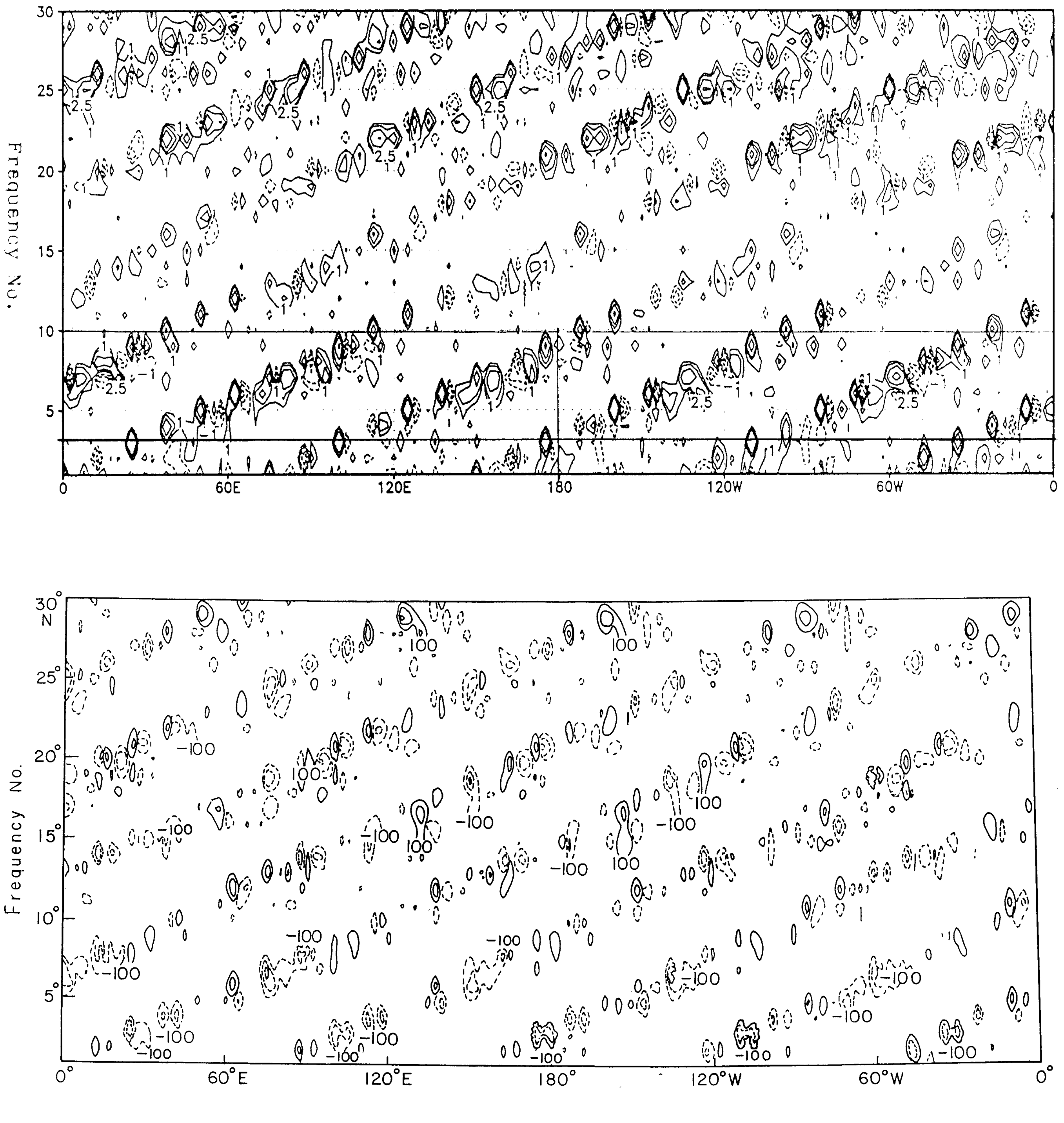

Figure 5. A latitude-frequency plot of baroclinic conversion from APE to KE for the summer monsoon 1994-1996 at 850 hPa over (a) tropics (20°S- 20°N) and (b) extra-tropics (20°N-60°N). The contours are labelled in units of 10^{-6} W kg^{-1}.

almost all frequency bands gain energy through this process in the tropics, unlike the extratropics where a loss of energy is noted. Fig.5(a) shows that the 10-45 day low frequency motions gain energy baroclinically. The baroclinic interactions are relatively strong over the region 0°E -180°E. During northern summer there exists Rossby waves which are highly convergent and for which there is no need for Ekman pumping in order to produce CISK. Further, during northern summer monsoon the Indian Ocean contains a large extent of warm water starting from the east coast of Africa. Positive SST anomaly remains over this region. Therefore, Fig.5(a) suggests that wave CISK process and strong sea surface temperature (SST) are the possible mechanisms for the strong energy interactions associated with low frequency waves in the lower troposphere over the west Pacific and Indian Ocean starting from east coast of Africa, where strong gradient of SST is observed. This is consistent with Chakraborty & Agarwal's (1997) results, which demonstrate the importance of baroclinic process in the tropics.

CONCLUSIONS

This paper reports a diagnostic study on the nonlinear triad interactive relationship between low and high frequency transients with 3 years of ECMWF 850 hPa and 200 hPa summertime wind fields, vertical velocity and temperature data with emphasis on the contrast between the extra-tropics and the tropics. Our main findings are follows :

(1) In the extratropics at the upper troposphere low frequency waves of period 45 day shows an overall gain of energy from its triad interactions with all other pairs of waves, particularly in the regions (20°N- 30°N and 50°N – 60°N). High frequency waves show an overall loss in this regard as well as through baroclinic in scale energy transfer.

(2) Overall in the tropics low frequency waves loose energy whereas high frequency waves gain energy mainly through barotropic process. The lower latitudes consistantly show sign reversals for both frequency bands. This is an indication that the nonlinear interaction of KE in the tropics takes the opposite direction of that in the extratropics.

(3)Tropical convection plays an important role for the maintenance of tropical intraseasonal oscillations.

(4) The role of time mean flow on the low frequency transient is found to be secondary, compared to the effect of the leading term due to nonlinear interactions in the upper and lower tropospheres.

(5) The role of 30 day oscillation is very much important in the upper tropospheric dynamics over the extra-tropics. Even in the lower troposphere low frequency oscillation of 30 day is very much interactive as compared to other oscillations but interaction is little weak as compared to upper troposphere.

(6) The results suggest that wave-CISK process and strong gradient of SST are the possible mechanisms associated with low frequency waves in the lower troposphere over the west Pacific and east coast of Africa.

The importance of baroclinic energy conversion in maintenance of low frequency variations has been demonstrated as secondary. This is somewhat expecting, since low frequency motions are observed to have an equivalent barotropic vertical structure, and therefore, are commonly thought to involve a smaller conversion of energy from APE to KE. However, the observational study by Krishnamurti et al. (1985) for the FGGE year showed evidence of strong baroclinic energy conversion is the primary energy source for low frequency oscillations in the extratropics. It is believed that the uncertainty is mostly restricted to the motions of the time mean and the annual cycle and therefore the importance of $\langle A(n).K(n) \rangle$ relative to other energy conversion term is established.

There is little disagreement about the interaction between the time mean flow and time transient eddies. It is speculated that the discrepancy between the earlier and the present studies is largely due to the fact, apart from the difference in analysis schemes, that the time mean flows in the earlier investigations is the annual mean flow while the representative of the summer time average is used in the present study.

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 wavenumbers 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. There is considerable room for further research in this area. Further investigations will be made of the nonlinear triad interactions in the frequecy domain in the following areas : (i) Intercomparison between energetics observed in the atmosphere and simulated in GCM experiments and (ii) Interannual variability of nonlinear triad interactions.

ACKNOWLEDGEMENTS

The authors thank Dr.G.B.Pant, Director of Indian Institute of Tropical Meteorology, and Dr. P.S. Salvekar, Deputy Director for their encouragement and for the facilities provided. The authors are grateful for the financial support received from DST sponsored project. And finally we acknowledge the work support partly provided by IBM solutions research centre, New Delhi.

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(Accepted 2002 August 31. Received 2002 August 12; in original form 2002 May 24)