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Aspects of ISOs during Indian Summer Monsoon as inferred from nonlinear divergent-rotational energy transfer

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ABSTRACT

The present study deals with the mathematical modeling designed to investigate the interactive dynamical and physical processes of seasonal mean monsoon circulation and intraseasonal oscillations (ISOs) on Madden Julian time scale associated with rotational and divergent transients during summer monsoon over Indian region based on nonlinear divergent-rotational kinetic energy (KE) exchanges into individual triad interactions in the frequency domain by the use of cross-spectral technique. NCEP wind analyses on a 2.5° square grid over the Indian region (EQ – 30° N and 40°E– 120°E) at 200 hPa and 850 hPa for 122 day period covering June to September 1996 are used.

The signature of ISO on Madden Julian time scale in the divergent component of the transient flow is captured prominently in the upper troposphere during summer monsoon. The coupling between the divergent component of the seasonal cycle and 30-60 day regional scale low frequency oscillation in the upper troposphere is very important for good monsoon over India. Apart from the seasonal cycle, the active monsoon associated with enhanced cyclonic low level vorticity and convection is reflected in the strong bimodal distribution of rotational KE interaction at the lower level 850 hPa. Seasonal cycle is found to be very much interactive due to the effect of both vorticity and divergence in the lower troposphere in building up rotational component of transient ISO during summer monsoon over India. The results permit one to hypothesize the impact of the ISO on the development of low level south westerlies dominated by rotational component is both local and remote and depends on the strength of the ISO with the seasonal cycle. The existence of strong rotational 30-40 day mode at 850 hPa indicates the presence of the Rossby mode which is highly nondivergent. Due to the latitudinal variation of earth's rotational effects, the conversion from transient divergent to rotational motions tends to be more pronounced to the north of 18°N on 30 -60 day time scale with the maximum gain of energy associated with 40 day period at about 22° N at 850 hPa.

INTRODUCTION

Observations have shown the presence of low frequency motions on the time scale of roughly 30 to 50 days. Different studies show that intra-seasonal oscillation on the Madden Julian time scale is an important feature during Indian summer monsoon. There is abundant evidence of frequency peaks in south Asian rainfall and wind in the same period band as the MJO (Murakami 1976; Yasunari, 1980, Yasunari & Tetsuzo 1981; Sikka & Gadgil 1980; Wang & Rui 1990; Julian & Madden 1981; Madden & Julian 1972, 1994). Close associations between the MJO and the active and break periods of the Indian and Australian monsoon have been focused by several authors. In the absence of a physical explanation for the MJO (Madden & Julian 1994) it is equally fair to state that the MJO is a result of an inherent instability of the coupled ocean atmosphere monsoon flow than to say that the active and break periods of the monsoon are the results of the MJO.

Based on Helmholtz theorem one can partition the horizontal wind field into rotational and divergent components. In the synoptic and the planetary scales the divergent wind components are much smaller than the rotational ones with the result that KE of the divergent wind is much less than the KE of the rotational wind. However previous studies have shown that despite its small magnitude it performs an important role in the atmospheric energy cycle. The role of differential heating is in its net generation of internal plus PE mainly in planetary scale of motion via the heating of relatively warmer air and cooling of relatively cooler air. If this does not take place, then the role of differential heating is dynamically negative. This generation of internal plus PE is usually accompanied by an ascent of warmer air and descent of colder air. This process transforms the generated internal and PE into divergent KE in different spatial and temporal scales. The interaction is the only means available for the rotational motion to receive KE from divergent motions over a closed domain. Thus it is believed that an involved energy transfer process from the differential heating to the eventual strong rotational motions of the monsoon is associated with different wavenumbers and frequencies.

Krishnamurti, Sinha & Mohanty (1995) studied the monsoon energetics through APE–divergent-rotational energy conversions in physical domain and showed the importance of nonlinear processes for maintenance of monsoon circulations. Chakraborty & Mishra (1993,1997a) and Chakraborty & Agarwal (1997) also investigated the divergent-rotational KE conversions by zonal wave plus wave-wave interactions due to action of different forcings in the wavenumber domain. Significant advances have been made in our understanding of the relative importance of different KE transfer mechanisms through which the tropospheric stationary and transient eddies are maintained in various wave categories during the summer monsoon over the tropics. There are important observational studies which strongly suggest that active, break and revival phases of the Indian summer monsoon are closely linked to the global equatorial low frequency waves on Madden Julian time scale. Therefore it is required to focus our aim in order to gain insight into the underlying interactive dynamics among rotational low and high frequency transients associated with planetary and synoptic scale disturbances and time mean flow that result from nonlinear divergent-rotational energy conversion due to the effects of Coriolis force, vorticity and divergence during monsoon over Indian region.

The low frequency intra-seasonal oscillations of the Indian summer monsoon represent a broad band spectrum with periods between 10 and 90 days but have two preferred bands of periods (Krishnamurti & Bhalme1976; Krishnamurti & Ardanuy 1980; Yasunari 1980), one between 10 and 20 days and the other between 30 and 60 days. The nonlinear transient divergent-rotational energy conversion due to different forcings is mainly associated with wavenumbers 1and 2 on the 30-45 day and 18-25 day time scales during tropical summer monsoon (Chakraborty & Agarwal 2000). As we shall see below, understanding intra-seasonal variations of the monsoon will require a better understanding of the nature of the coupling between the seasonal cycle and 30-60 day low frequency intra-seasonal oscillations associated with its rotational and divergent components in the lower and upper tropospheres respectively. The upper tropospheric planetary scale divergent motion associated with low frequency oscillation of 30-60 days plays important role for the performance of tropical and Indian summer monsoon too. It is coupled with low level regions of 30-60 day wind circulation which is mainly dominated by its rotational component. Chakraborty & Agarwal (2000) examined the dynamical mechanism of low frequency monsoonal transients through divergent-rotational nonlinear energy transfer due to different forcings during tropical summer monsoon.

The above studies suggest that much remains to be explained regarding the nature of the coupling between the seasonal development of the monsoon circulation and the rotational and divergent components of ISO on Madden Julian time scale. The other questions arise: How and to what extent intra-seasonal oscillations influence the seasonal mean? What are the dynamical mechanisms responsible for the maintenance of rotational and divergent transients associated with different low and high frequencies in the lower and upper troposphere respectively which affect the performance of Indian summer monsoon?

The current study deals with mathematical modeling designed to investigate the dynamical mechanisms and role of low frequency rotational and divergent transients on Madden Julian time scale through nonlinear divergent-rotational KE exchanges into individual triad interactions in the frequency domain by use of cross spectral technique. First time attempt has been made to understand the problem of low frequency transient rotational and divergent waves over Indian region during summer monsoon by using this technique. The computations are carried out to identify the dominant triad interactions by divergent-rotational KE conversions due to the action of Coriolis force, vorticity and divergence and the related underlying interactive dynamics for the development of seasonal monsoon circulation and intra-seasonal oscillations of rotational and divergent transients. The interactions between rotational seasonal mean and transient low frequency oscillations have been analysed too for Indian summer monsoon.

FORMULATION

Following Chen (1980) and Chakraborty & Mishra (1993), the expression for energy conversion C in the wavenumber domain between *K2* and *K3* may be expressed as

$$C = C\,(0) + \sum_{n=1}^{N} C(n) \qquad (1)$$

where

$$C(0)=\int_{\mu 1}^{\mu 2}\left[f\cdot\bar{u}2\cdot\bar{v}3+\bar{\zeta}\cdot\bar{u}2\cdot\bar{v}3-\frac{1}{2}\bar{D}\cdot\bar{u}2\cdot\bar{u}2\right]d\mu/\left[2(\mu 2-\mu 1)\right]$$

and f is the Coriolis parameter.

C(0) represents the contribution from the interaction between the zonal rotational and divergent motion:

$$C(n)=\int_{\mu 1}^{\mu 2}\left[\bar{\zeta}\sum_{i=1}^{2}\left(u2(n,i)\cdot v3(n,i)-u3(n,i)\cdot v2(n,i)\right)+\bar{u}2\sum_{i=1}^{2}\left(\zeta(n,i)\cdot v3(n,i)\right)\right.$$

$$\left.+\bar{v}3\sum_{i=1}^{2}\left(\zeta(n,i).u2(n,i)\right)\right]d\mu/\left[4(\mu 2-\mu 1)\right]-\int_{\mu 1}^{\mu 2}\left[\bar{D}\sum_{i=1}^{2}\left(u2(n,i)\cdot u2(n,i)+v2(n,i)\cdot v2(n,i)\right)\right.$$

$$\left.+\bar{u}2\sum_{i=1}^{2}\left(D(n,i)\cdot u2(n,i)+D(n,i)\cdot u2(n,i)\right)\right]d\mu/\left[8(\mu 2-\mu 1)\right]$$

$$+\int_{\mu 1}^{\mu 2}\left[f\sum_{i=1}^{2}\left(u2(n,i)\cdot v3(n,i)-u3(n,i)\cdot v2(n,i)\right)+\sum_{i=1}^{2}\zeta(n,i)\cdot C\zeta(n,i)\right.$$

$$\left.-\frac{1}{2}\sum_{i=1}^{2}D(n,i)\cdot CD(n,i)\right]d\mu/\left[4(\mu 2-\mu 1)\right] \qquad (2)$$

Where $C\zeta(n,i)$ and $CD(n,i)$ $(i=1,2)$ are, respectively, the Fourier coefficients of the following nonlinear terms:

$$C\zeta=u2'\cdot v3'-u3'\cdot v2'$$
$$CD=u2'\cdot u2'-v2'\cdot v2' \qquad (3)$$

The eddy energy conversions between divergent and rotational flow can be written in the frequency domain by expressing all the terms in R.H.S of the eqn.(2) in terms of frequency cospectra in a manner similar to Chakraborty & Agarwal (2000).

The relevant final formulations are given below:

$$C(n)=CFWW(n)+CVZW(n)+CVWW(n)+CDZW(n)+CDWW(n) \qquad (4)$$

where, *C(n)* is the energy conversion between rotational and divergent parts of motions associated with the frequency n and positive *C(n)* denotes the energy conversion from divergent to rotational flow. *CFWW, CVWW* and *CDWW* are exchanges of energy between divergent and rotational motion by wave-wave interaction due to Coriolis force, vorticity and divergence respectively. The terms in the R.H.S. of the equation (4) are expressed as

$$CFWW(n)=f\left[\left(U2TC_n.V3TC_n+U2TS_n.V3TS_n\right)-\left(U3TC_n.V2TC_n+U3TS_n.V2TS_n\right)\right]/2 \qquad (5)$$

$$CVZW(n)=\bar{\zeta}\left[U2TC_n.V3TC_n+U2TS_n.V3TS_n-U3TC_n.V2TC_n-U3TS_n.V2TS_n\right]/2$$
$$+\left[\bar{U}2(\zeta TC_n.V3TC_n+\zeta TS_n.V3TS_n)+\bar{V}3(\zeta TC_n.U2TC_n+\zeta TS_n.U2TS_n)\right]/2 \qquad (6)$$

$$CDZW(n)=-\bar{D}\left[U2TC_n.U2TC_n+U2TS_n.U2TS_n+V2TC_n.V2TC_n+V2TS_n.V2TS_n\right]/2$$
$$-\bar{U}2\left[\left(DTC_n.U2TC_n+DTS_n.U2TS_n\right)+\left(DTC_n.U2TC_n+DTS_n.U2TS_n\right)\right]/2 \qquad (7)$$

$$CVWW(n)=\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\+\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(\zeta TC_n.U2TC_r.V3TC_s-\zeta TC_n.U3TC_r.V2TC_s\right)$$

$$+\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\+\sum_{r-s=n}\\-\sum_{r-s=-n}\end{array}\right|\left(\zeta TS_n.U2TS_r.V3TC_s-\zeta TS_n.U3TS_r.V2TC_s\right)$$

$$+\frac{1}{2}.\left|\begin{array}{l}-\sum_{r+s=n}\\+\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(\zeta TC_n.U2TS_r.V3TS_s-\zeta TC_n.U3TS_r.V2TS_s\right)$$

$$+\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\-\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(\zeta TS_n.U2TC_r.V3TS_s-\zeta TS_n.U3TC_r.V2TS_s\right) \qquad (8)$$

$$CDWW(n)=-\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\+\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(DTC_n.U2TC_r.U2TC_s+DTC_n.V2TC_r.V2TC_s\right)$$

$$-\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\+\sum_{r-s=n}\\-\sum_{r-s=-n}\end{array}\right|\left(DTS_n.U2TS_r.U2TC_s+DTS_n.V2TS_r.V2TC_s\right)$$

$$-\frac{1}{2}.\left|\begin{array}{l}-\sum_{r+s=n}\\+\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(DTC_n.U2TS_r.U2TS_s+DTC_n.V2TS_r.V2TS_s\right)$$

$$-\frac{1}{2}.\left|\begin{array}{l}+\sum_{r+s=n}\\-\sum_{r-s=n}\\+\sum_{r-s=-n}\end{array}\right|\left(DTS_n.U2TC_r.U2TS_s+DTS_n.V2TC_r.V2TS_s\right) \qquad (9)$$

The notations used are defined in Appendix .

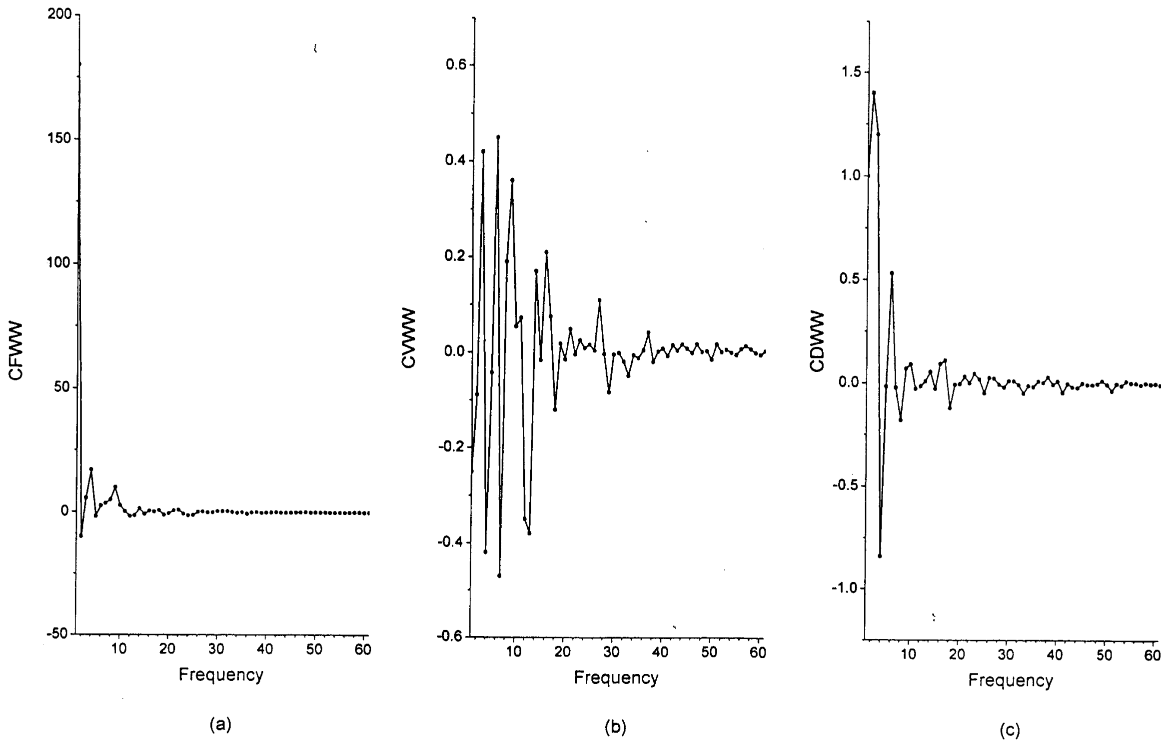

Figure 1. The Spectra of Intra-frequency Nonlinear Energy Exchanges between Divergent and Rotational Flows due to a) Coriolis force, b) Vorticity and c) Divergence respectively at 850hPa. Units 10^{-7} Wkg^{-1}.

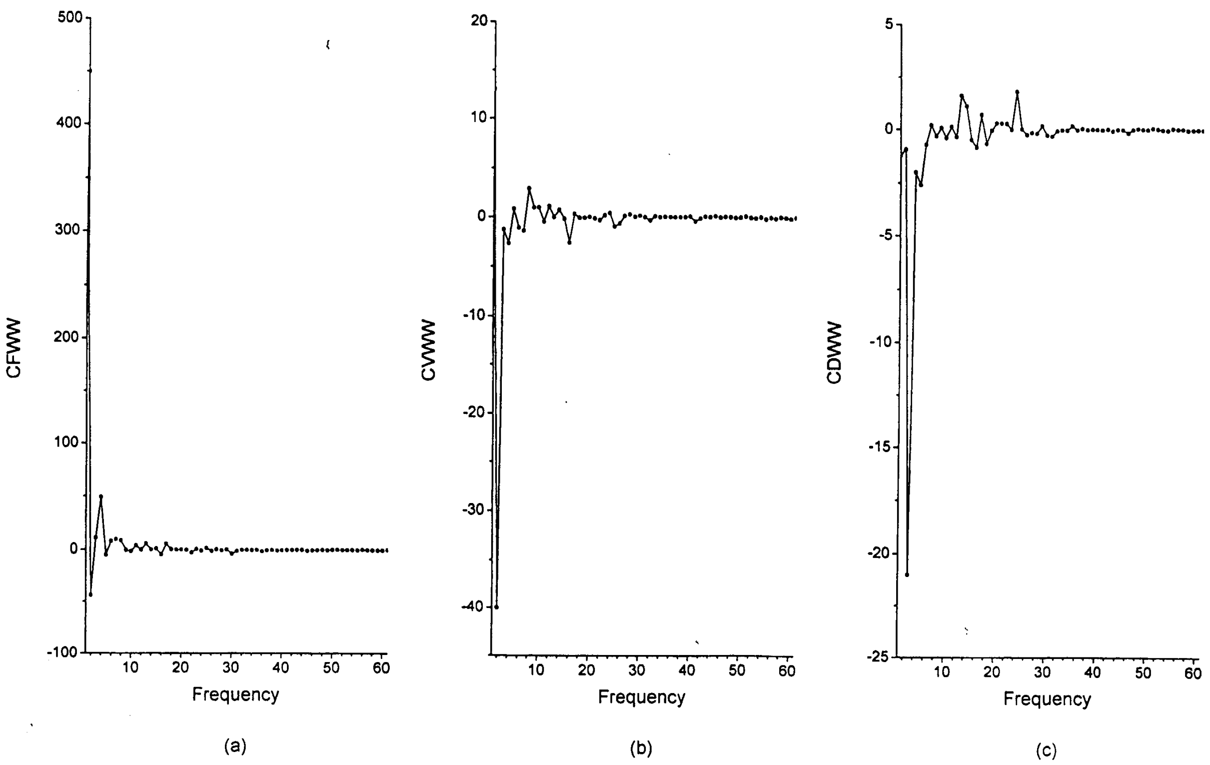

Figure 2. Same as in Fig.1 except for 200hPa.

DATA AND COMPUTATIONS

NCEP daily wind analyses on a 2.5 degree square grid over the Indian region (0-30° N and 40°-120°E) at 200hPa and 850hPa for 120 day period covering June, July, August and September 1996 are used. Total wind is separated into divergent and rotational components using the method suggested by Tandon (1992). Stationary (120 day average field) and transient (departure from 120 day average field) are obtained. To separate high frequency transients, the low frequency transients and time mean flow from the total 850hPa and 200hPa wind fields, a temporal Fourier decomposition is used. Nonlinear triad interactions and quasi-linear interactions by divergent–rotational KE conversions in the frequency domain due to the action of Coriolis force, divergence and vorticity are obtained by computations of a different frequency co-spectra and cross–bispectra from the equations (5)-(9).

RESULTS

In the present study the energy reservoirs are regrouped as motions of seasonal mean, the seasonal 120 day cycle, low frequency intra-seasonal oscillations of 30-60 day period, 10-20 day period and high frequencies, which represent the synoptic time scales shorter than 10 days. Observed daily data were used for all calculations. So Nyquist frequency corresponds to a period of 2 days and oscillations with periods shorter than 2 days are subject to aliasing. The grouping is only subjective and is meant to provide a simplified view of the energetics in the frequency domain. The regional and global aspects of monsoonal low frequency oscillations are mainly associated with 850hPa and 200hPa levels. As in Chakraborty & Mishra (1993) and Chakraborty & Agarwal (1997) 200hPa and 850hPa are considered in the present study as the representative levels for upper and lower tropospheric monsoon studies over the Indian region. Divergent-rotational (χ-ψ) energy transfers in the wavenumber/frequency domain mainly consists of three terms; due to the effect of Coriolis force, vorticity and divergence. (χ-ψ) interactions due to the action of vorticity and divergence are resolved into two components; Seasonal mean-time transient and intra-frequency interactions whereas due to effect of Coriolis force it has only intra-frequency interactions. The interaction parameters have been integrated over relatively wide spectral frequency bands (from 2-120 days) to represent the high and low frequency transients.

Interaction between seasonal cycle and low frequency oscillations is an important mechanism for good monsoon over India. Decomposition of divergent-rotational kinetic energy transfer by nonlinear interactions into individual triad contributions due to the action of vorticity and divergence at 200hPa and 850hPa are performed in the frequency domain over seasonal cycle to 2 day cycle. In the present study the lowest frequency corresponds to 120 day period. Therefore interaction of this frequency with frequencies of periods higher than 120 day is not included. Thus nonlinear interaction of this frequency is not complete in that sense. The results reveal that transient ISO of period 60 day loses energy in the lower troposphere due to the action of vorticity by nonlinear divergent-rotational triad interaction with other pairs of frequencies whereas rotational transients of 40 day and 20 day cycles receives energy due to the same process. <3,4,1> and <6,7,1> show very strong triad interactions due to vorticity in the lower troposphere. They transfer rotational KE at the rate of 2.3×10^{-8} WKg^{-1} and 3.3×10^{-8} WKg^{-1} respectively. The impact of the ISO on the development of the low level southwesterlies is both local and remote and depends on the strength and phasing of the ISO with the seasonal cycle (Li et al. 1999). Seasonal cycle of 120 day period is playing an important role in transferring energy to the rotational low frequency oscillations by the way of interacting with other low frequencies.

At 200hPa divergent component of ISO on Madden Julian time scale of 30-60 days gain enormous amount of energy when it interacts with other pairs of oscillation by divergent- rotational interaction due to divergence in the upper troposphere (Tables not shown). A minus sign indicates the energy transfer from rotational flow to divergent flow and transient flow to seasonal mean. Particularly 40-day oscillation of divergent motion is found to be very much interactive and gains maximum energy through the triad interaction <3,4,1> which contributes at the rate of $-74\times10^{-8}WKg^{-1}$.

It is noticed that the interaction among seasonal cycle and other low frequency oscillations make the divergent ISO strong by extracting energy from the seasonal cycle through the interaction processes. As it is mentioned earlier that the seasonal cycle is found to be very strong in its rotational and divergent components. Very special kind of interaction is involved with <2,1,1> , contribution of which to 60 day cycle is at the rate of $-20 \times10^{-8} WKg^{-1}$. It may so happen that one seasonal cycle of certain parameter interacts with the same cycle of another parameter. Also divergent component of seasonal cycle can interact with rotational component of the same cycle.

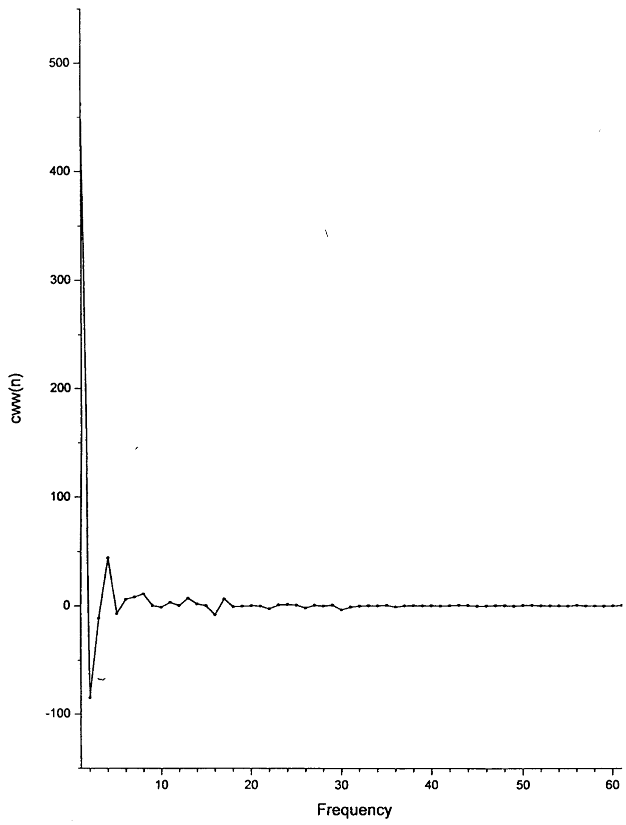

Figure 3. Spectra of Intra-frequency Nonlinear KE Exchanges between Divergent and Rotational Flows due to Different Forcings at 200hPa. Units 10^{-7} Wkg^{-1}.

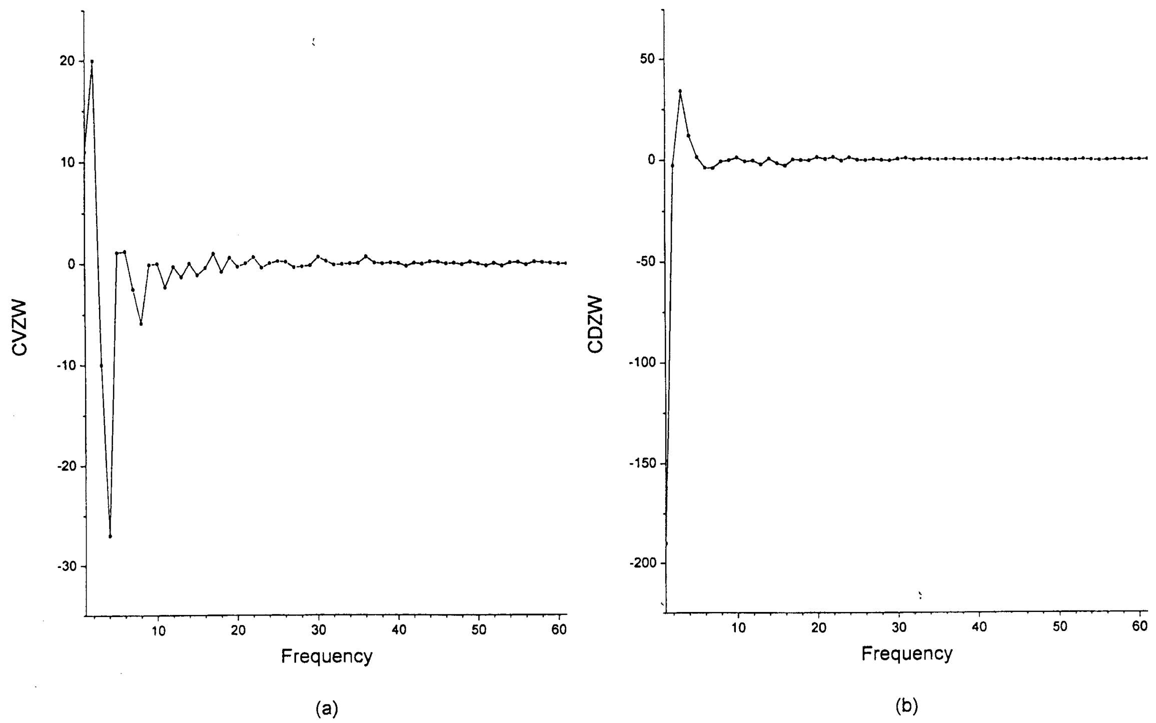

Figure 4. Spectra of Nonlinear KE Exchanges between Divergent and Rotational Flows by Time Mean-Time Transient interactions due to a) Vorticity and b) Divergence respectively at 200hPa. Units 10^{-7} Wkg^{-1}.

Even rotational or divergent motion of the seasonal cycle involved with the same parameter can interact among them and energy can be passed to or extracted from a third oscillation if they are in different latitudes. Therefore present results reveal the important role of triad divergent-rotational interaction responsible in building up strong divergent motion associated with ISO during Indian summer monsoon. Several studies have focused on the coupling between the seasonal cycle and low frequency intra-seasonal fluctuations. Murakami, Chen & Xie (1986) suggested a possible nonlinear interaction between seasonal cycle and a group of low frequency (24-90 day) oscillations. They also suggested a possible nonlinear interaction between seasonal cycle and 30-50 day mode of divergent circulations over the Indian monsoon region.

Spectra of intra-frequency nonlinear energy exchanges between divergent and rotational flows due to Coriolis force, vorticity and divergence at 850hPa and 200hPa are shown in Fig.1 and Fig.2 respectively. Coriolis force is the most dominating forcing in nonlinear energy transfer due to (χ-ψ) interactions as far as rotational seasonal cycle and 30-40 day cycle at 850hPa and divergent 60 day cycle at 200hPa are concerned. Due to vorticity effect the (χ-ψ) interaction shows a primary and a secondary peak in the rotational energy transfer, one at about 20 days and the other at 40 days at 850hPa. The same interaction process carries strong signal in 40-60 day divergent oscillation at 200hPa. Upper tropospheric divergent flow on Madden Julian time scale and the seasonal scale divergent flow receive enormous amount of energy by (χ-ψ) interaction due to the effect of divergence. Thus the coupling between the divergent component of the seasonal cycle and 30-60 day regional scale low frequency oscillation in the upper troposphere is very important for good monsoon over India. Vorticity and divergence effects work well in establishing 40-60 day divergence circulation but when Coriolis forcing comes into play it transfers rotational energy and 40-60 day divergent cycle becomes little weak at 200hPa during Indian summer monsoon. The overall effects of intra-frequency oscillations make 60 day divergent cycle strong in the upper troposphere (Fig.3). Coriolis forcing is an important factor in the mechanism of building up of seasonal rotational cycle and 30-40 day cycle, whereas due to vorticity and divergence the transfer of energy to 40 day and 40-60 day cycles respectively are enhanced at 850hPa. In every individual dynamical process the nonlinear interaction shows a secondary peak around 10-20 day cycle in the lower troposphere. The rotational seasonal cycle and 30-40 day cycles are the most prominent modes in the lower troposphere during summer monsoon over Indian region. Thus the results permit one to hypothesise that the impact of the ISO on the development of the low level southwesterlies dominated by rotational component is both local and remote and depends on the strength of the ISO with the seasonal cycle.

Interaction between the seasonal mean flow and other transient oscillations are considered to be very crucial mechanism for maintenance of monsoon circulation, ISO and high frequency disturbances over Indian region as well as over tropics. Seasonal cycle and 60 day oscillation enhance seasonal mean divergent flow when the former two interact with the latter due to divergence in the upper troposphere whereas the effect is the other way due to the action of vorticity (Fig.4). Fig.5 shows the intensification of 60 day cycle in divergent flow in the upper troposphere by nonlinear intra-frequency interactions and the interaction between seasonal mean and time transient through (χ-ψ) coversions. From Fig.6 it is noticed that the flow is barotropically unstable to the rotational low frequency disturbances in the lower troposphere. Rotational component of seasonal cycle and 40-60 day cycle are extracting good amount of energy when they interact with seasonal mean through divergent-rotational energy conversions due to the action of both vorticity and divergence in the lower troposphere. Even the rotational component of 10-20 day cycle and synoptic time scale disturbances of period 3-7days extract energy from the seasonal mean flow due to the action of vorticity. Dennis, Hartmann & Michelsen (1989) demonstrated 5-7 day spectral peak associated with monsoon lows. The spectra of time mean-time transient interaction by (χ-ψ) conversion due to the action of low level vorticity exhibit different rotational low frequency oscillations and synoptic scale oscillations. These may be the manifestations of active and break spells of the monsoon arising out of interaction of seasonal mean and ISOs during summer monsoon. Intra-frequency interactions and time mean-time transient interactions together intensify rotational seasonal cycle, 30-40 day oscillations and secondary low frequency oscillation of about 15 day period at 850hPa (Fig.7). The existence of strong rotational 30-40 day oscillation at 850hPa indicates the presence of the Rossby mode which is highly nondivergent.

The distributions of energy conversion of transient divergent to rotational KE, due to the action of Coriolis force as a function of latitude and frequency for Indian summer monsoon are given in Fig.8 at 850hPa. These demonstrate that due to the latitudinal variation of the earth's rotational effects, the conversion from transient divergent to rotational

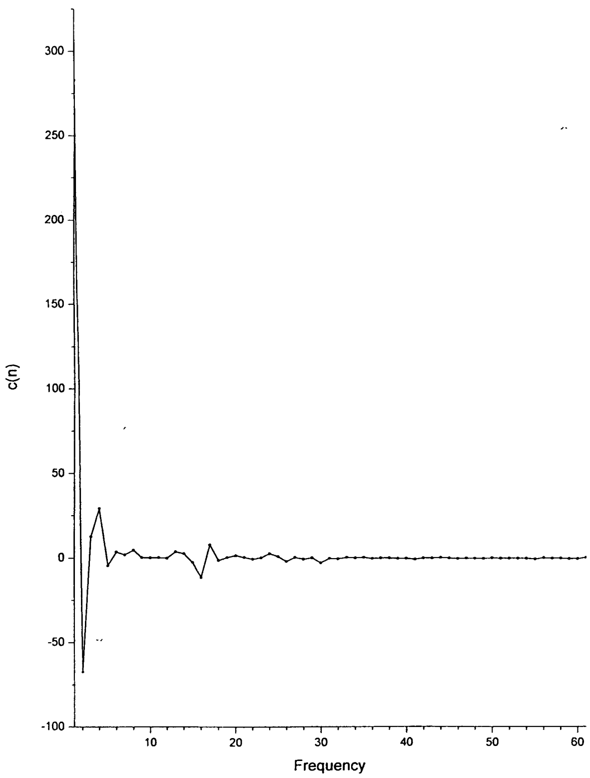

Figure 5. Spectra of Nonlinear KE Exchanges between Divergent and Rotational Flows by Time Mean-Time Transient and Intra-frequency Interactions due to Different Forcings at 200hPa. Units 10^{-7} Wkg^{-1}.

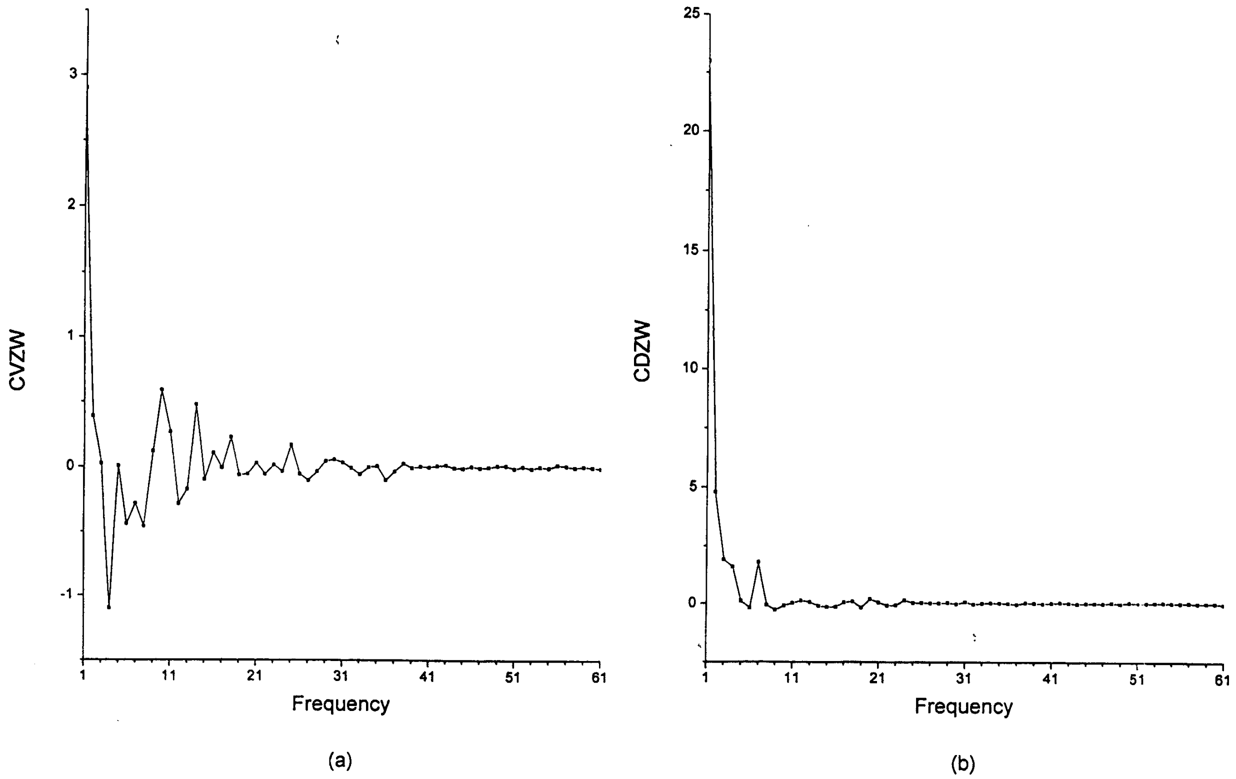

Figure 6. Same as in Fig. 4 except for 850hPa.

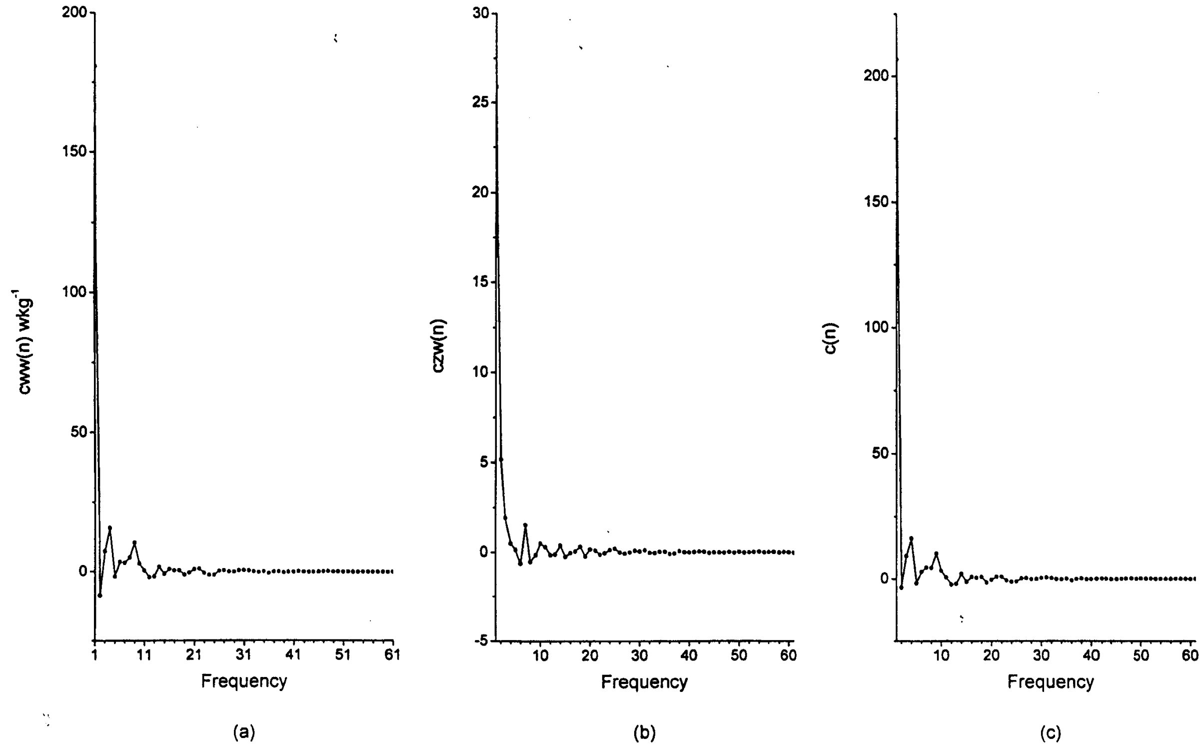

Figure 7. Spectra of Nonlinear KE Exchanges between Divergent and Rotational Flows by a) Intra-frequency Interactions b) Time Mean-Time Transient Interactions and c) Total nteractions respectively at 850hPa. Units 10^{-7} Wkg^{-1}

motions tends to be more pronounced to the north of 18°N on 30-60 day time scale with the maximum gain of energy associated with 40 day period at about 22°N at 850hPa which is the mean latitude of movement of monsoon depression. Chakraborty & Agarwal (1996) noticed that north of 20°N low frequency waves of period 30 to 92 days gain energy during tropical summer monsoon. It is known that strong monsoon periods are characterized by an anomalously strong cyclonic circulation at low levels centred near 20°N over India and stretching eastward over Burma and Indochina toward the gulf of Tonkin. They are weaker in the near equatorial latitudes.

KE conversions by divergent-rotational interactions due to the action of vorticity and divergence as function of latitude and frequency at 850 hPa and 200 hPa are illustrated in Fig.9 and Fig.10 respectively. Vorticity effect intensifies the rotational component of 30-60 day transient oscillation around 12-20°N at 850hPa. Northward migration of the low level westerly moisture flux between 10°N and 20°N also helps to activate the Indian summer monsoon. We notice another cycle of 10-20 days in rotational transient motion due to vorticity in the lower troposphere. At 850hPa transient rotational flow of 30-60 day period gain substantial amount of KE over 10-20°N when they interact nonlinearly with other frequencies. 40 day cycle is very much pronounced. Transient divergent cycle of 30-40 days is receiving energy from rotational flow through (χ-ψ) interaction due to divergence around 15-25°N at 200hPa. 40 day cycle is very much pronounced here also. Particularly, in the north of 20 N the effects of vorticity and divergence forcings are complementary in building the transient divergent component of ISO on Madden Julian time scale at 200 hPa. The seasonal mean flow lose energy to transient rotational ISO due to divergence over the belt 15 N-25N (not illustrated).

CONCLUSIONS

The present study deals with mathematical modeling designed to investigate the interactive dynamical and physical processes of seasonal mean monsoon circulation and low frequency oscillations on Madden Julian time scale associated with rotational and divergent transients during monsoon over Indian region through nonlinear divergent-rotational KE exchanges into individual triad interactions in the frequency domain by use of cross spectral technique. The interactions between rotational and divergent components of seasonal mean and transient low frequency oscillations have been analysed too. NCEP daily wind analyses on a 2.5 degree square grid over

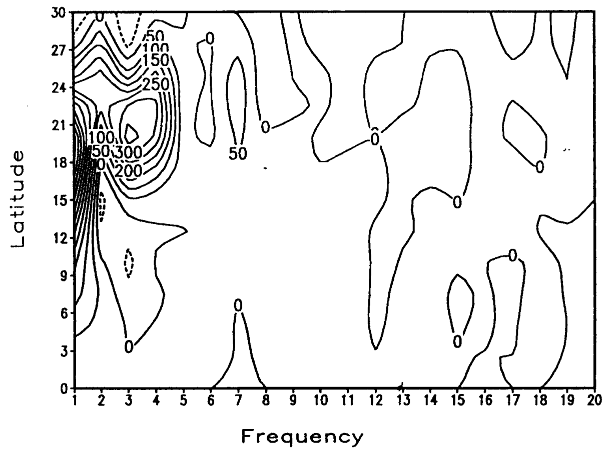

Figure 8. A Latitude–Frequency plot of Intra-frequency Nonlinear KE Exchanges due to Corioilis force at 850hPa. The contours are labelled in units of 10^{-7} Wkg$^{-1.}$

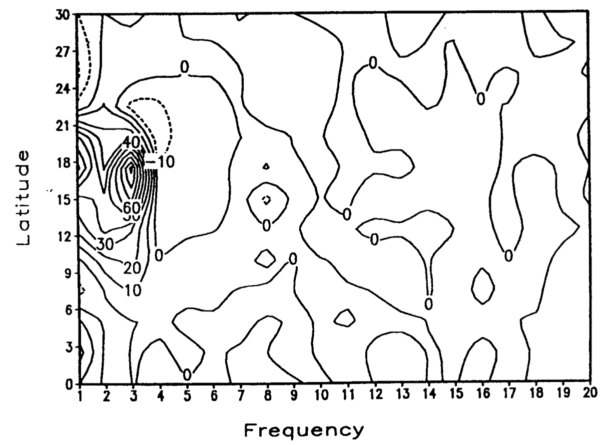

Figure 9. A Latitude–Frequency plot of Intra-frequency Nonlinear KE Exchanges due to Vorticity at 850hPa. The contours are labelled in units of 10^{-7} Wkg^{-1}.

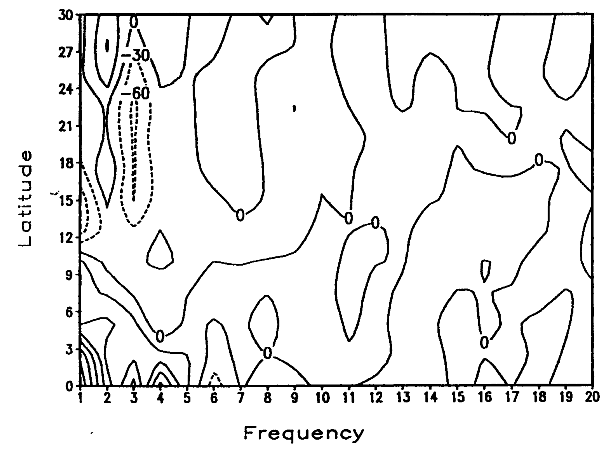

Figure10. A Latitude-Frequency plot of Intra-frequency Nonlinear K.E. Exchanges due to Divergence at 200 hPa. The contours are labeled in units of 10^{-7} Wkg^{-1}.

the Indian region (0-30°N and 40°-120°E) at 200hPa and 850hPa for 120 day period covering June, July, August and September 1996 are used.

The signature of intra-seasonal oscillations on Madden Julian time scale in the divergent component of the transient flow is captured prominently in the upper troposphere during summer monsoon. Apart from the seasonal cycle, the active monsoon associated with enhanced cyclonic low level vorticity and convection is reflected in the strong bimodal frequency distribution of rotational KE interaction at the lower level 850hPa. It is seen that transient rotational ISO of period 60 day lose energy in the lower troposphere due to the action of vorticity by nonlinear divergent-rotational triad interaction with other pairs of frequencies whereas those of periods 40 days and 20 days receiving energy due to the same process. At 200hPa divergent component on Madden Julian time scale of 30-60 days gain enormous amount of energy by the process of divergent-rotational energy conversion due to intra-frequency interaction. Contribution of seasonal cycle towards the maintenance of divergent ISO through nonlinear process is significant over the Indian monsoon region. Thus the coupling between the divergent component of the seasonal cycle and 30-60 day regional scale low frequency oscillation in the upper troposphere is very important for good monsoon over India. Coriolis force is the most dominating forcing in nonlinear energy transfer due to (χ-ψ) interactions as far as rotational seasonal cycle, 30-60 day cycle at 850hPa and divergent 60 day cycle at 200hPa are concerned. The results permit one to hypothesise the impact of the ISO on the development of the low level south westerlies dominated by rotational component is both local and remote and depends on the strength of the ISO with the seasonal cycle. Seasonal cycle and 40 day oscillation enhance seasonal mean divergent flow when the former two interact with the latter due to divergence in the upper troposphere The existence of strong rotational 30-40 day mode at 850hPa indicates the presence of the Rossby mode which is highly nondivergent. The flow is barotropically unstable to the rotational low frequency disturbances at 850 hPa. Due to the latitudinal variation of earth's rotational effects, the conversion from transient divergent to rotational motions tends to be more pronounced to the north of 18°N on 30-60 day time scale with the maximum gain of energy associated with 40 day period at about 22°N at 850hPa. North of 20°N the effects of vorticity and divergence forcings are complementary in building the transient divergent component of ISO on Madden Julian time scale at 200hPa. The seasonal mean flow lose energy to transient rotational ISO due to divergence over the belt 15°N-25°N.

Although the investigation with present data sets and methodology have provided reasonably consistent results in explaining the broad features of ISO on Madden Julian time scale associated with the Indian monsoon, we believe, that until they are confirmed by the use of more accurate data sets, the results must be considered tentative. Since the high frequency motions are 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, of not quantitative, only semi-qualitative. There is considerable room for further research in this area. It would also be of interest to examine about how and to what extent the intra-seasonal oscillations influence the rotational and divergent components of seasonal mean and its inter-annual variability of the Indian summer monsoon. The impact of rotational transient ISO on ENSO is another important area of research in the frequency domain.

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APPENDIX

λ	longitude
ϕ	latitude $\mu=\sin\phi$
ζ	vorticity
D	divergence
ψ	stream function
χ	velocity potential
$\nabla\chi$	grad of χ
$X2TC_n$,$X2TS_n$	Fourier cosine and sine coefficients of rotational transient field $X2$ for frequency n respectively
$X3TC_n$,$X3TS_n$	Fourier cosine and sine coefficients of Divergent transient field $X3$ for frequency n respectively
$\overline{X} = \frac{1}{2T}\int_{-T}^{+T} X dt$	time mean of $\boldsymbol{X}$
$XT = X - \overline{X}$	departure of X from the time mean
$K2(n)$	rotational KE for frequency n
$K3(n)$	divergent KE for frequency n

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