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Effects of Coriolis force, vorticity and divergence on nonlinear energy conversions during different phases of July 1979 monsoon

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सार — 850 है.पा. और 200 है.पा. की 10° द., 30° उ. अक्षांशीय पेटी पर जुलाई 1979 की मानसून की विभिन्न स्थितियों के दौरान फुरिये स्पेक्ट्रल प्रक्षेत्र की घूर्णात्मक और अपसारी प्रवाहों की गतिज ऊर्जा तथा कोरिओलिस बल की क्रिया से इनके बीच उत्पन्न होने वाले अरैखिकीय ऊर्जा में परिवर्तन, अपसरण एवं भ्रमिलता और इसके पश्चात् इनका स्थिर और क्षणिक गतियों में विभाजित होने का परिकलन तथा अध्ययन इसमें किया गया है। यह ज्ञात हुआ है कि कोरिओलिस बल की क्रियाशीलता के कारण अरैखिकीय घूर्णन प्रसारी गतिक ऊर्जा में परस्पर आदान-प्रदान की क्रिया होती है जिसके कारण उष्णकटिबंध के दोनों स्तरों पर सभी तरह की स्थिर और क्षणिक तरंगें उत्पन्न होती हैं । हमारे परिणाम यह दर्शाते हैं कि 850 है.पा. पर क्षणिक गतिकी के दौरान तरंगों में होने वाली अन्योन्यक्रिया महत्वपूर्ण भूमिका निभाती है। भिन्नता के कारण क्षेत्रीय तरंगों में होने वाली अन्योन्यक्रिया से घूर्णन प्रसारी गतिक ऊर्जा में होने वाले परिवर्तन तथा कोरिओलिस बल के कारण तरंगों में होने वाली अन्योन्यक्रिया के 200 है. पा. पर क्रमशः स्थिर भूमंडलीय घूर्णन के लिए और क्षणिक सिनॉप्टिक स्केल तरंगों के लिए महत्वपूर्ण माना गया है । यह अनुमान लगाया गया है कि 200 है.पा. पर कोरिओलिस बल और भ्रमिलता के कारण अरैखिकीय ऊर्जा में होने वाले पररिवर्तन परस्पर प्रतिकूल हैं। परिणामों के कारण अरैखिकीय ऊर्जा में होने वाले परिवर्तन परस्पर प्रतिकूल हैं। परिणामों से यह सिद्ध होता है कि ऊर्जा रूपान्तरण परिघटना पूरी तरह से दाब धनत्वी नहीं है। मानसून के सक्रिय होने के विभिन्न स्तरों पर अभूविक्षेपी प्रभाव के महत्व का भी पता चला है।

ABSTRACT. Kinetic energy (KE) of the rotational and divergent flows and the nonlinear energy conversion between them due to the action of Coriolis force, divergence and vorticity, partitioning further into stationary and transient motions are computed in the Fourier spectral domain during different phases of July 1979 monsoon over the latitudinal belt 10°S-30°N at 850 and 200 hPa and studied. It is found that nonlinear divergent to rotational KE exchange due to the action of Coriolis force is the primary contributor for all categories of stationary and transient waves at both the levels over tropics. Our results indicate that in the transient scale dynamics the wave-wave interaction plays a dominant role at 850 hPa. Divergent to rotational KE conversion by zonal-wave interaction due to divergence and wave-wave interaction due to Coriolis force are identified as important mechanisms for maintenance of rotational stationary planetary and transient synoptic scale waves respectively at 200 hPa. It is inferred that nonlinear energy conversions due to Coriolis force and vorticity oppose each other at 200 hPa. The results support that the energy conversion phenomenon may not be entirely barotropic. The importance of ageostrophic effect at different stages of monsoon activities is also shown.

Key words — Nonlinear phenomenon, Energy conversion, Ageostrophic effect.

1. Introduction

Based on Helmholtz Theorem, one can partition the horizontal wind field into rotational and divergent components. The divergent wind components associated with the synoptic and planetary scales are much smaller than the rotational ones. Thus, the kinetic energy (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 atmospheric energy cycle.

Chen and Wiin-Nielsen (1976) have investigated the KE budget of divergent and rotational flows in the atmosphere. Their theoretical arguments and numerical computations show that the available potential energy (PE) is converted into KE of the divergent flow and then into the KE of rotational flow. Inspite of the relatively large sources and sinks of divergent KE, the levels of divergent KE remain low. This suggests low residence time for the divergent KE and it plays a catalytic role in the conversion of available PE to the KE of the rotational flow. This view was further confirmed by grid point calculation of energy transfer between divergent and rotational KE (Lambert 1989).

Chen (1980) investigated rotational-divergent KE exchanges in the tropics and subtropics in terms of zonal wave number in the area between 15°S and 42°N at 200 hPa during June, July and August of 1967 and 1972. He suggested that the computation of conversion of divergent KE to rotational KE using the horizontal winds may provide alternative method of evaluating the generation of KE in the tropics.

Krishnamurti and Ramanathan (1981), in his study over limited area, found that the KE of the divergent circulation does not increase much with time. This energy is shown to be transferred rapidly to the rotational motion *via* a number of interaction functions. The orientation of the divergent flow is shown to be of prime importance in these transfers during the onset, active, break and revival periods of the monsoons.

It is well known that adiabatic nonlinear normal mode initialization (NMI) drastically depletes the tropical divergent circulation and diabetic NMI can lead to inconsistent divergent field although it is dynamically balanced (Puri 1987). Hence it is important to investigate the spectral interaction between rotational and divergent components of motion in the tropics with uninitialized data.

Chakraborty and Mishra (1993, 1996) also investigated the divergent-rotational KE conversion by zonal-wave plus wave-wave interactions due to the action of different forcings together for maintenance of stationary and transient waves in the upper and lower troposphere over tropics during July 1979. In their study the contributions to divergent-rotational KE exchanges by zonal-wave and wave-wave interactions due to Coriolis force, vorticity and divergence effects were not separated.

In this study the nonlinear transfer of KE from divergent to rotational flow due to the action of Coriolis force, vorticity and divergence were investigated and discussed. The relative importance of different kinds of nonlinear interaction functions during different phases of monsoon for July 1979 over global tropics (10°S - 30° N) at 200 hPa and 850 hPa for transient and combined (stationary plus transient) eddies were also examined.

2. Data and analysis

The eddy KE conversions between divergent and rotational flow can be expressed in terms of zonal-wave number (n) in a manner similar to Chakraborty and Mishra (1993).

$$C(n) = CFWW(n) + CVZW(n) + CVWW(n) + CDZW(n) + CDWW(n) \qquad (1)$$

where, C is the eddy energy conversion between rotational and divergent parts of motions and positive $C(n)$ denotes the energy conversion from divergent to rotational flow, $CFWW$ is exchange of energy between divergent and rotational motion by wave-wave interaction due to Coriolis force, $CVWW$ and $CDWW$ represent the same due to action of vorticity and divergence respectively, $CVZW$ and $CDZW$ denote the KE conversion between divergent-rotational motion by zonal-wave interaction due to vorticity and divergence effects respectively. The expressions used to compute $CFWW$, $CVZW$, $CVWW$, $CDZW$, $CDWW$ are contained in Appendix B.

The basic data used for this study were the spherical harmonics coefficients of ψ and χ with a triangular truncation of 42 waves computed from the reanalysed First GARP (Global Atmospheric Research Program)

TABLE 1

Divergent-rotational KE exchanges by zonal-wave (Z-W) and wave- wave (W-W) interactions due to the effects of Coriolis force, vorticity and divergence in units of 10^{-6} Wkg^{-1} in various wave categories at 200 hPa

Zonal Wave no.	Coriolis effect		Vorticity effect				Divergence effect			
	Stationary	Transient	Stationary		Transient		Stationary		Transient	
	W-W	W-W	Z-W	W-W	Z-W	W-W	Z-W	W-W	Z-W	W-W
1-4	13	23	5.2	4.1	1.6	–0.73	24	–3.1	–0.84	1.3
5-14	7.2	30	–0.67	–1.2	–1.6	–2.3	–1.0	0.68	–1.1	–1.4
15-24	0.04	0.92	–0.30	–0.12	–0.26	–0.54	–0.19	0.10	0.24	–0.04

Global Experiment (FGGE) IIIb wind data on the 1.875° latitude-longitude grid of 1200 UTC for 31-day period covering July 1979 at 850 and 200 hPa. The Fourier coefficients of ψ, χ, rotational ($u2$, $v2$) and divergent ($u3$, $v3$) components of wind, vorticity (ξ) and divergence (D) were obtained from the spherical coefficients of ψ and χ for wave numbers 1-24 at 2° latitude grid interval in the belt 10°S - 30° N. Stationary (31 - day average field) and transient (departure from 31 - day average field) components are obtained. The KE and all nonlinear conversion spectra of stationary motion are computed by using the July average values. All the energy conversion terms for transient and combined (stationary plus transient) motions are computed for each day by using daily transient and observed fields respectively and their monthly average values are obtained.

3. Results

3.1. *Divergent-rotational KE conversion in wave number categories*

In nonviscous and adiabatic atmosphere, the sum of internal, potential and kinetic energy is conserved. Further, the summation over the nonlinear wave interactions individually vanishes for kinetic energy and available PE and does not require the absence of heating and friction. The role of differential heating is in its net generation of internal plus PE mainly in the 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

TABLE 2

Same as in Table 1 except for 850 hPa

Zonal Wave no.	Coriolis effect		Vorticity effect				Divergence effect			
	Stationary	Transient	Stationary		Transient		Stationary		Transient	
	W-W	W-W	Z-W	W-W	Z-W	W-W	Z-W	W-W	Z-W	W-W
1-4	9.2	9.9	–0.05	0.98	0.00	0.16	–1.8	0.51	–0.04	–0.04
5-14	–3.0	4.2	–0.23	1.4	0.08	0.18	–0.99	0.37	0.03	0.10
15-24	–0.37	1.3	–0.04	–0.04	0.04	–0.09	–0.06	0.11	–0.03	0.06

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 the divergent KE in different scales. The interaction is the only means available for the rotational motion to receive KE from the divergent motions over a closed domain. Thus we believe an involved energy transfer process from the differential heating to the eventual strong rotational motions of the monsoons is associated with different wave numbers.

Divergent-rotational KE exchanges by nonlinear interactions due to the effects of Coriolis forces, vorticity and divergence in three wave number categories namely, 1-4 (planetary scale waves), 5-14 (synoptic scale waves) and 15-24 (subsynoptic scale waves) at 200 and 850 hPa are shown in Tables 1 & 2 respectively. All the calculations are shown at 200 and 850 hPa only because they are considered as the representative levels for upper and lower troposphere respectively for monsoonal studies (Chakraborty and Mishra 1993, 1996). Divergent-rotational energy conversion consists of mainly three terms due to effect of Coriolis force, vorticity and divergence. Divergent-rotational energy exchanges due to vorticity and divergence effects are partitioned into zonal-wave and wave-wave interactions, whereas that due to Coriolis effect has only wave-wave component. Each component is broken into its standing and transient parts.

By examining the tables it is found that nonlinear energy exchanges due to the action of Coriolis force is the major contributor to the divergent-rotational KE conversion $C(n)$ for all categories of stationary and transient waves at both the levels over tropics.

Energy conversions by wave-wave interaction due to effects of Coriolis force, vorticity and divergence are found to be positive for transient synoptic scale waves at 850 hPa. These processes transfer enormous amount of energy from divergent to rotational flow in this scale of waves. Thus in the transient synoptic scale wave dynamics wave-wave interaction plays a dominant role in the lower troposphere.

At 850 hPa conversion by zonal-wave interaction due to vorticity and divergence is found to be negative for most of the planetary and subsynoptic scale stationary and transient waves. These terms are not able to counteract the strong positive effect of the terms due to wave-wave interaction. It is important to note that at 850 hPa divergent to rotational KE transfer by zonal-wave interaction due to the effect of vorticity plays a key role for maintenance of transient subsynoptic scale waves, whereas this kind of energy transfer is insignificant for planetary scale transient waves.

It is also seen from the tables that all the nonlinear KE conversion terms due to different forcings are stronger at 200 hPa compared to those at 850 hPa. This result is expected on the basis that rotational and divergent eddy KE for stationary and transient motions reach their maximum value at 200 hPa (Chakraborty and Mishra 1993). It can be concluded from our results that at 200 hPa divergence plays primary role for stationary rotational planetary scale waves as they receive enormous amount of energy through energy conversion process from divergent planetary flows by zonal-wave interaction. For transient synoptic scale waves, wave-wave interaction due to the action of Coriolis force transfers maximum amount of KE from divergent to rotational component at 200 hPa. But this interaction is comparable to the value of planetary scale transient waves.

Earlier studies (Chakraborty and Mishra 1993, Desai and Mishra 1993) showed that in the upper troposphere over tropics as well as over globe synoptic scale waves are highly transient. The present computation for eddy transient KE is in agreement with the earlier finding. Therefore, it is speculated that transient rotational components lose energy when they interact with stationary divergent component in planetary scale, motion due to the action of Coriolis force. It is also seen from Table 1 that for stationary planetary scale waves, zonal-wave and wave-wave interactions due to the effect of vorticity are equally important for large positive divergent-rotational energy transfer at 200 hPa. It can be concluded from the results that in general the wave-wave KE exchanges from divergent to rotational component due to Coriolis force effect is the most dominating interaction process for all categories of transient waves and at both the levels.

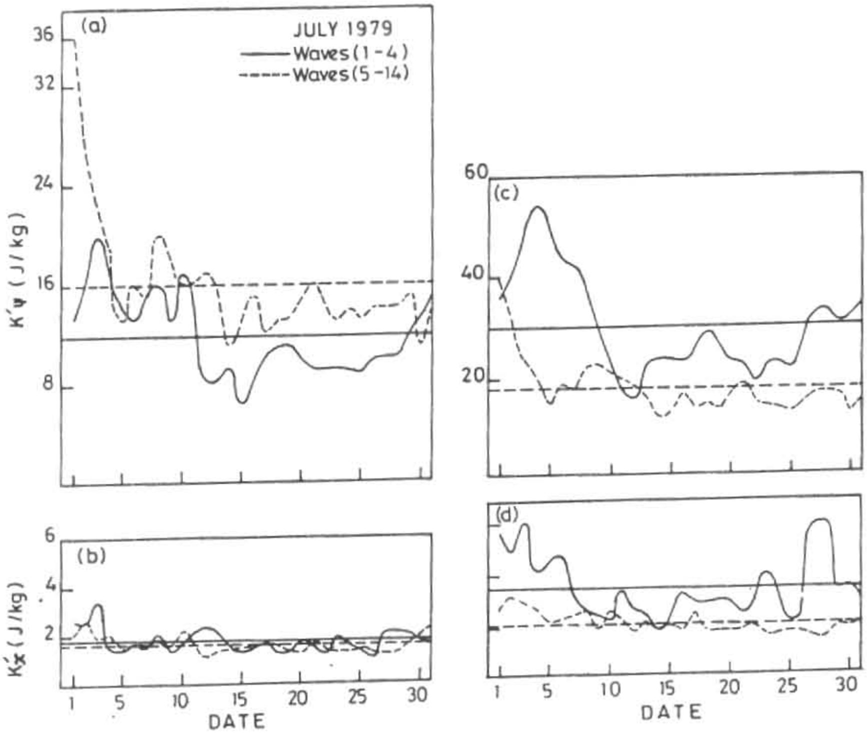
3.2. *Time evolution of KE and its conversion*

Time series of different components of interactions for transient and combined waves are plotted and analysed to have illustrative view of monsoon circulation and monsoon synoptic scale systems over tropics in July 1979. Following Krishnamurti and Ramanathan (1981) & Krishnamurti and Surgi (1985) the course of the evolution of July 1979 monsoon has following important phases:

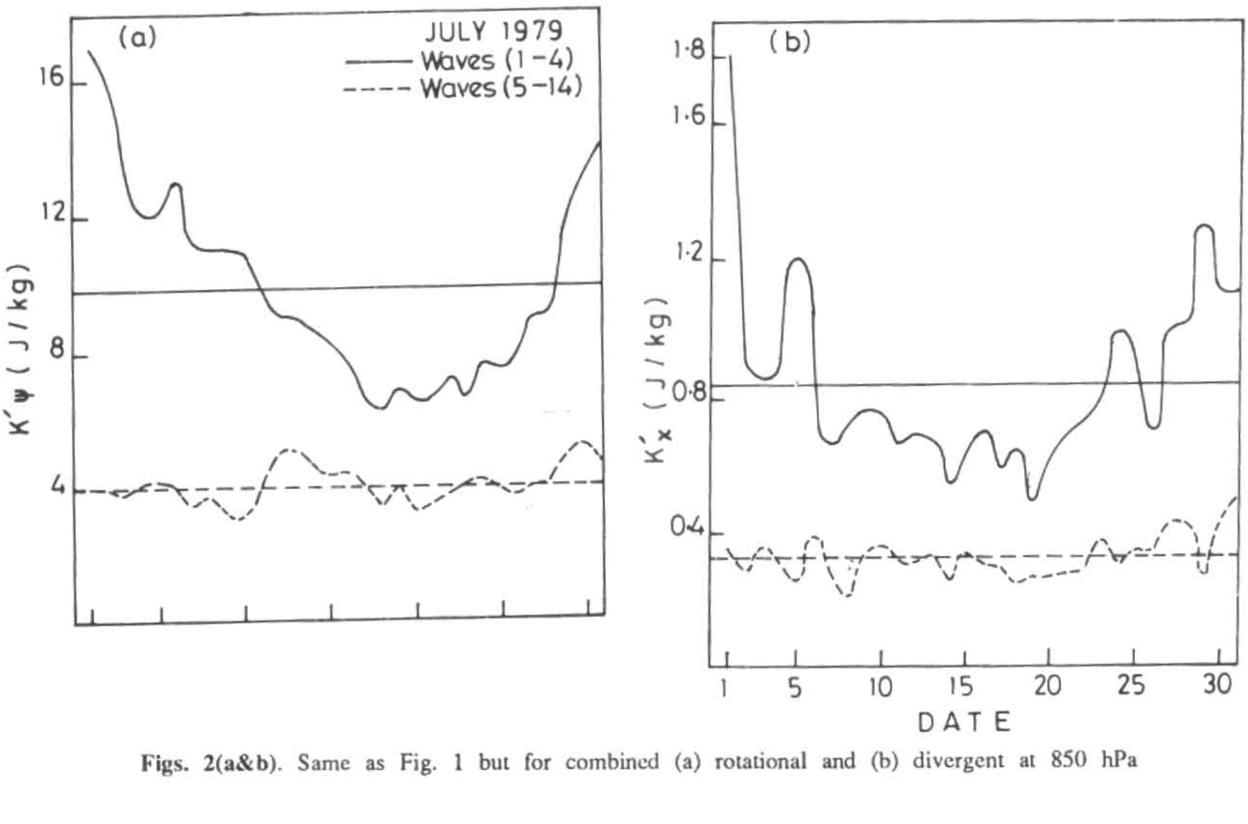
(*i*)	3-7 July	monsoon depression
(*ii*)	10-25 July	break monsoon
(*iii*)	Last week of July	revival of monsoon; tropical depression

The time series of rotational and divergent KE of transient and combined flows associated with planetary scale waves (1-4) and synoptic scale waves (5-14) at 200 hPa are shown in Figs. 1(a-d) and those at 850 hPa for combined waves are shown in Figs. 2(a & b). The expression for computation of rotational and divergent KE spectra are given in Appendix B. It is noticed that a period of decay of KE between 10 and 25 July coincides with a period of break in monsoon rain. This is clearly seen particularly for combined rotational planetary scale waves at 850 hPa. The time series of combined divergent waves at 850 hPa shows similar behaviour. The time series of rotational and divergent KE of combined waves look similar to those of transient waves at 200 hPa.

Almost all the series exhibit primary peak during the first week of July and a relatively weak secondary peak during the last week of July. These periods coincide with the period of strong monsoon depression and perhaps less intense tropical depression respectively. From Fig. 1(a), it is seen that the rotational transient synoptic scale waves have higher values compared to planetary waves on each day of July 1979 at 200 hPa particularly during active phase. Therefore, transient motion is dominated by synoptic scale eddies in the tropics during monsoon.



Figs. 1 (a-d). Time series of rotational and divergent KE of transient and combined flows associated with planetary scale waves (1-4) and synoptic scale waves (5-14) at 200 hPa



Figs. 2(a&b). Same as Fig. 1 but for combined (a) rotational and (b) divergent at 850 hPa

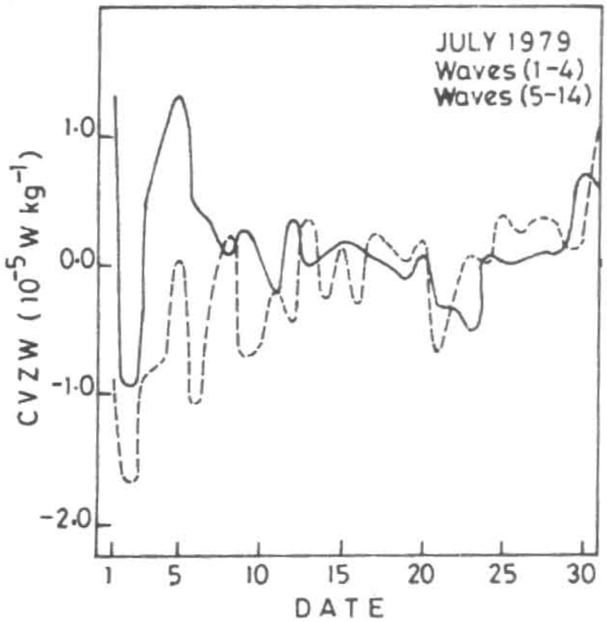


Fig. 3. Divergent-rotational KE conversions by zonal-wave interaction due to vorticity at 200 hPa, for transient planetary and synoptic waves

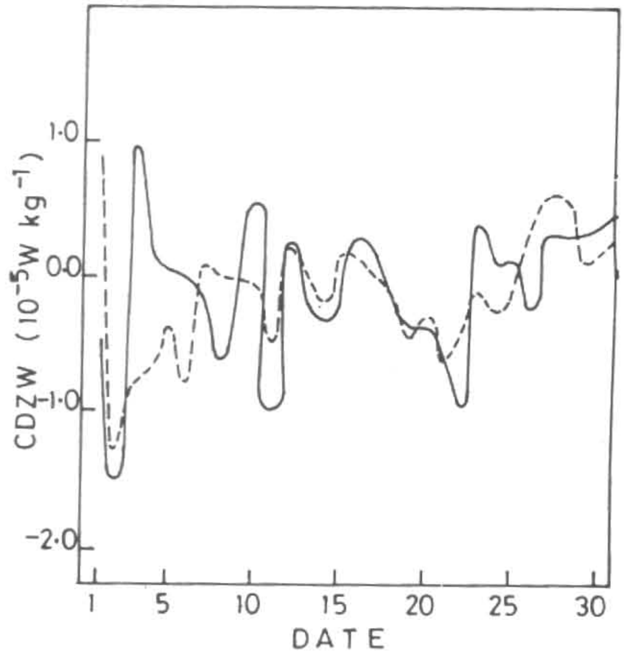


Fig. 4. Divergent-rotational KE conversions by zonal-wave interaction due to divergence at 200 hPa, for transient planetary and synoptic scale waves

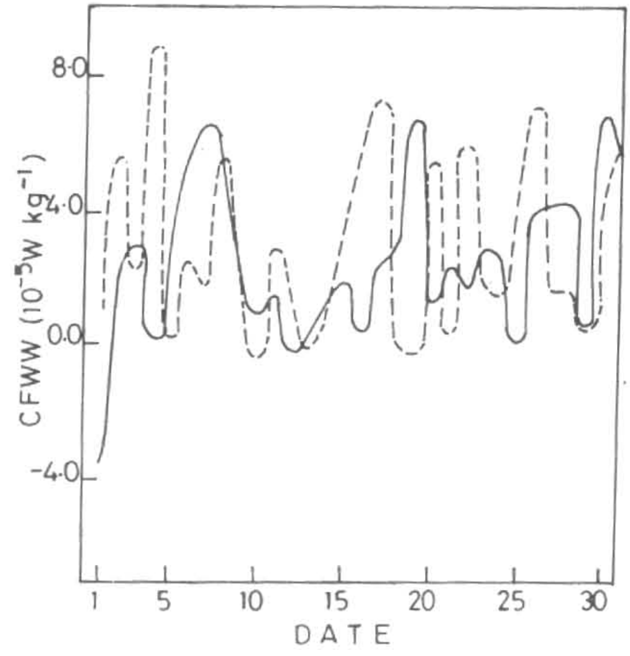
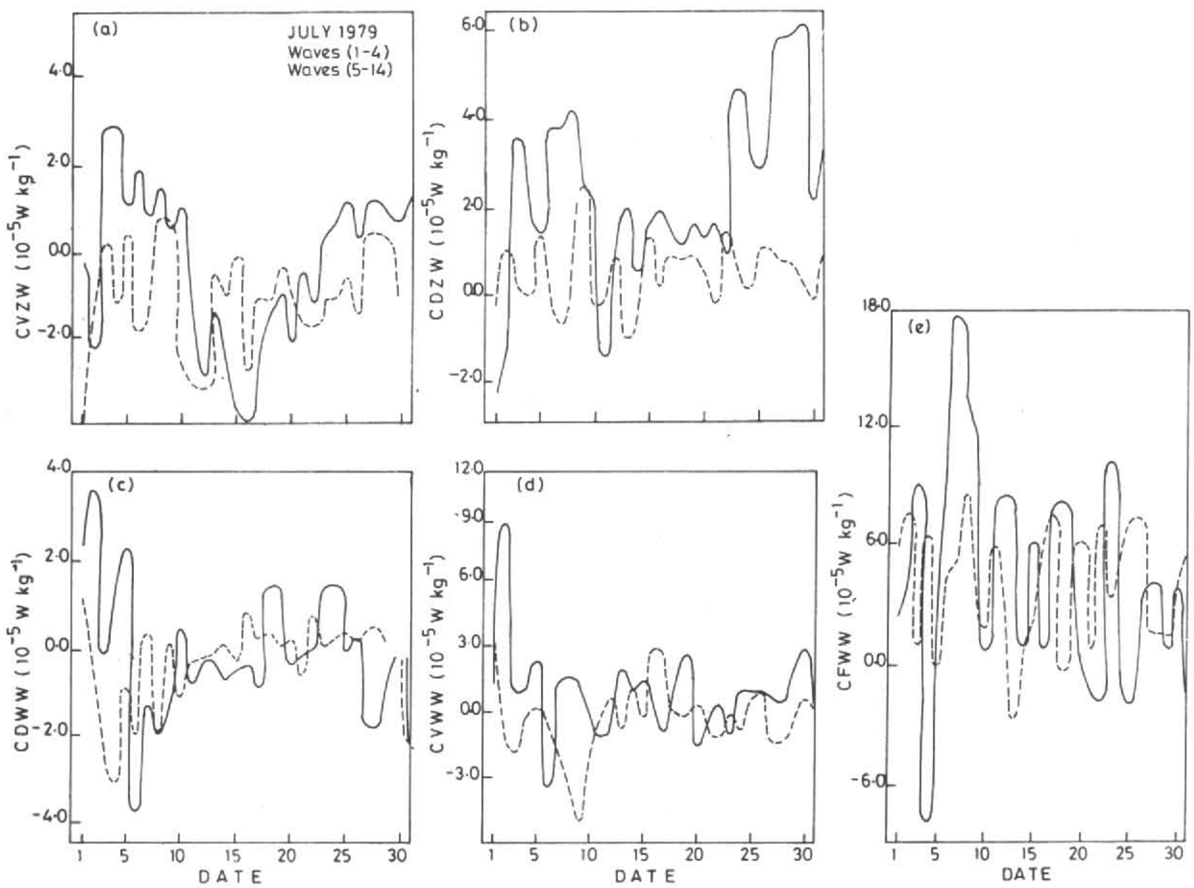
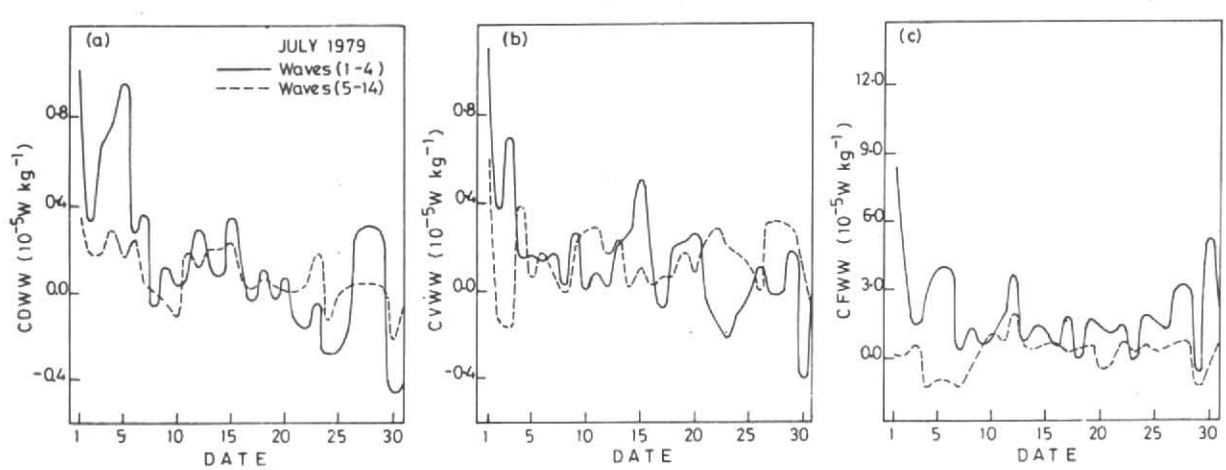


Fig. 5. Divergent-rotational KE conversions by wave-wave interaction due to Coriolis force, for transient planetary and synoptic scale waves

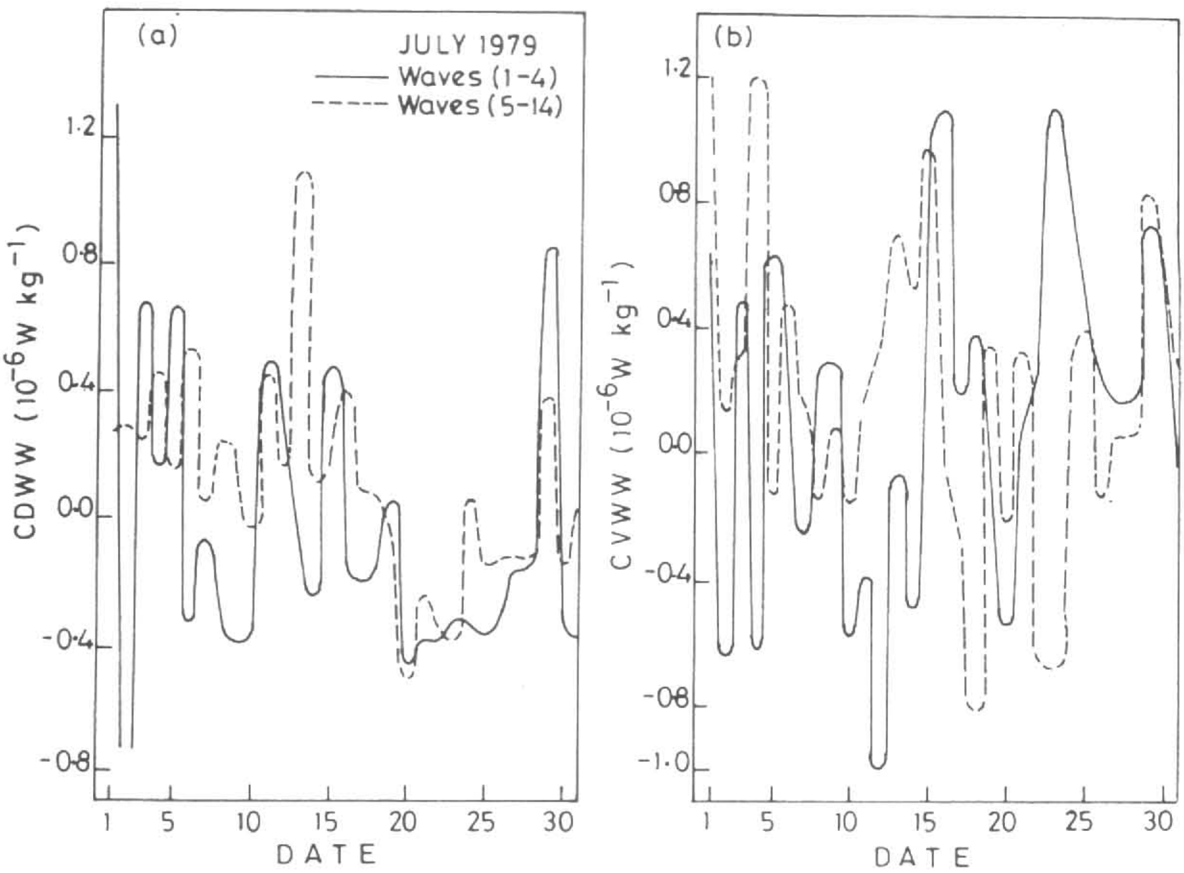
The behaviour of nonlinear KE interaction of transient departures from the mean circulation has long been of interest to researchers, ranging from long period variations, breaks, individual synoptic systems etc. It is seen from Fig. 3 that for the transient planetary waves, divergent-rotational KE



Figs. 6(a-e). Divergent-rotational KE conversions by zonal-wave interaction due to (a) vorticity and (b) divergence and that by wave-wave interaction due to (c) divergence, (d) vorticity and (e) Coriolis force effects, for combined waves at 200 hPa



Figs. 7(a-c). Divergent-rotational KE conversions by wave-wave interaction due to (a) divergence, (b) vorticity and (c) Coriolis force effects, for combined planetary and synoptic scale waves at 850 hPa



Figs. 8(a&b). Divergent-rotational KE conversions by wave-wave interaction due to (a) divergence and (b) vorticity for transient planetary and synoptic scale waves at 850 hPa

conversion by zonal wave interactions is found to be positive in the first and last week of July at 200 hPa due to increase of vorticity when monsoon and tropical depressions were present respectively and it shows its maxima around 5 July. The divergent-rotational KE conversions by zonal-wave interaction due to divergence effect for transient planetary and synoptic scale waves is similar to that due to vorticity effect at 200 hPa (Fig. 4). For synoptic scale transient waves the conversions are found to be positive in the last week of July only. Fig. 5 shows that wave-wave interactions due to Coriolis force effect transfer enormous amount of energy from divergent to rotational component for transient planetary and synoptic scale waves. A period of increase of this interaction associated with transient planetary and synoptic scale waves due to the action of the Coriolis force coincides with the periods of depression and active phase of monsoon while the period of decrease coincides with that of break.

This interaction term depends on the orientation of $\nabla\psi$ and $\nabla\chi$ and turned out to be the leading one among the interaction terms for transient waves. Krishnamurti and Ramanathan (1981) examined the orientation of $\nabla\psi$, $\nabla\chi$ during the active, depression and break periods and the impression he got is that $\nabla\psi$ does not change its orientation as much as $\nabla\chi$ does. The active and depression periods seem to coincide with nearly zonal orientation for the transient ψ and χ isopleths associated with planetary and synoptic scale waves. The break period perhaps can be characterised by a zonal orientation for the ψ isopleths while a more meridional (northwest to southeast) orientation for the χ isopleths is related to transient planetary and synoptic scale eddies. It appears that the χ isopleths undergo very interesting fluctuations in their orientations. This is obviously related to the manner in which they extract energy from the differential heating *via* vertical overturnings in different wavenumber regimes and pass it on to the rotational modes without substantially

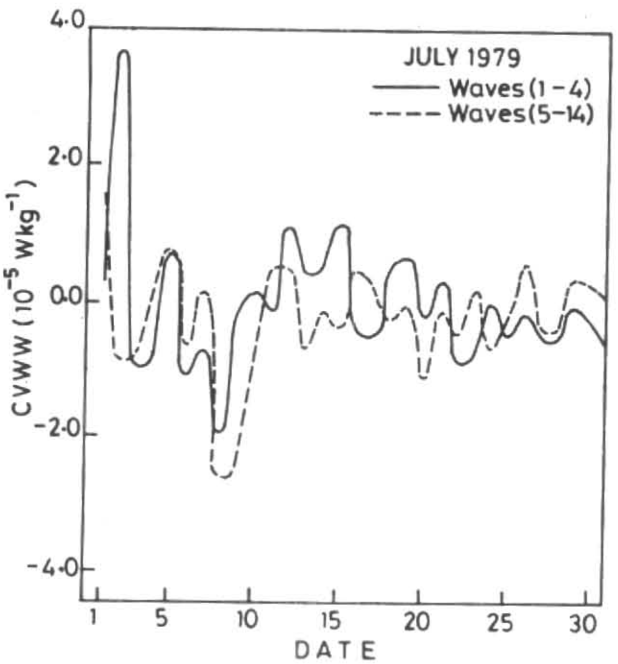


Fig. 9. Divergent-rotational KE conversions by wave-wave interaction due to vorticity for transient planetary and synoptic scale waves at 200 hPa

altering their own energy K_χ. This suggests that the phenomenon may not be entirely barotropic.

For combined waves the pattern of time series of divergent - rotational KE by zonal-wave and wave-wave interactions due to vorticity, divergence and Coriolis force effects respectively are similar to those of transient waves at 200 hPa but as expected the conversions in the combined category are very strong [Figs. 6 (a- e)]. The contributions by zonal-wave interaction due to divergence is more prominent than that due to vorticity for combined waves, whereas those are of equal importance for transient waves at different phases of the July 1979 monsoon. It is not expected that the conversions due to Coriolis force, divergence and vorticity effects are equally important at different phases of July monsoon circulation. Based upon computations and scale analysis (Philips 1963), Chen and Wiin-Nielsen (1976) showed that the energy conversion associated with divergence term is, in general, one order of magnitude smaller than that associated with Coriolis force and vorticity terms. It is perhaps that over tropics at 200 hPa horizontal divergence is large during the period of monsoon depression and revival of monsoon which makes the conversion particularly by zonal-wave interaction due to the divergence term more significant than that due to vorticity term.

The computation of divergent-rotational KE conversions by nonlinear interactions due to the action of Coriolis force, vorticity and divergence effects at 850 hPa for transient and combined waves showed that the interaction terms are one order less compared to those in the upper troposphere during different phases of monsoon. Large positive divergent-rotational KE conversions by wave-wave interaction due to Coriolis force, vorticity and divergence effects are noticed during the period of monsoon depression for combined planetary scale waves [Figs. 7(a-c)]. It is also noticed from Figs. 8(a&b) that transient divergent synoptic scale waves transfer substantial amount of energy to its rotational counterpart by the way of wave-wave interaction due to divergence and vorticity during the period of different phases of monsoon at 850 hPa. At this level., divergence and vorticity effects are more or less equally important for divergent-rotational KE conversion.

The most dominant component is Coriolis term at all the stages of monsoon activities during July 1979 at 850 and 200 hPa. During break period some of interaction terms associated mostly with synoptic scale waves show small positive values of energy conversion. This may be due to the influence of synoptic systems at other than monsoon region in tropics.

It may be noticed that in this study the contribution of stationary-transient interactions have not been taken into account for computation of divergent-rotational energy conversion due to zonal-wave and wave-wave interactions for transient and stationary motions. Therefore, time variation of transient KE of planetary and synoptic scale wave categories do not clearly reflect the fluctuation of monsoon as revealed by the combined (transient + stationary) KE.

The magnitude of divergent-rotational energy exchange term due to Coriolis effect depends on the orientation of the vectors $\nabla\psi$ and $\nabla\chi$. The energy exchanges go from the divergent to rotational modes throughout almost 31-day period of July with a primary maximum during monsoon depression period and a secondary maximum during revival of monsoon for synoptic scale combined and transient waves at 200 hPa as is seen from Figs. 5 & 6(e). Therefore, $\nabla\psi \cdot \nabla\chi > 0$, *i.e.*, the angle between vectors $\nabla\psi$ and $\nabla\chi$ is less than $\pi/2$. As our region of consideration is 10°S to 30°N, over the major region $f > 0$. Same conclusion holds good for planetary scale combined and transient waves at 850 hPa. It appears that the effect of monsoon depression associated with preferred synoptic scale transient and combined flows might have been diluted with group of waves 5-14 over global tropics. A large region of $f \nabla\psi \cdot \nabla\chi > 0$ might have been evolved during the period 1 - 31 July 1979 over tropical belt. The development of the strong winds associated with planetary scales monsoon circulation and synoptic scale disturbances were related to the evolution of $\nabla\psi$, $\nabla\chi$ vectors over the tropical belt.

Divergent-rotational KE conversion by zonal-wave and wave-wave interactions for transient and combined synoptic scale waves at 200 hPa [Figs. 3 & 9] due to relative vorticity effect have negative sign at most of the time over tropics. The sign is related to the fact that the monsoonal current in the tropics has a negative relative vorticity in the upper troposphere. The term is not able to counteract the positive effect of the leading term due to Coriolis effect. Thus the nonlinear energy conversions due to Coriolis force and vorticity oppose each other.

The result of our computations show clearly that divergent-rotational KE conversion due to Coriolis effect is the major contributor to $C(n)$ in the tropics. The contributions to that due to vorticity and divergence effect are secondary. It has been shown by Chen and Wiin-Nielsen (1976) that Coriolis effect is the only term by which conversion between divergent and rotational KE can takç place in a quasi-geostrophic model. However, contributions due to vorticity and divergence effects are also appreciable for upper tropospheric stationary planetary scale waves. This indicates the importance of ageostrophic effect in the planetary scale dynamics over tropics.

4. Summary and conclusions

The 200 hPa and 850 hPa wind, vorticity and divergence fields for the tropics (10°S - 30°N) in July 1979 were used to study KE of rotational and divergent flows, the nonlinear energy conversion between them by zonal-wave and wave-wave interactions due to the action of Coriolis force, divergence and vorticity and their time evolutions for transient and combined (stationary plus transient) flows. The relative importance of different nonlinear interaction functions during different phases of monsoon for July 1979 at upper and lower troposphere for transient and combined eddies were also examined in three wave categories.

It is found that nonlinear energy exchange due to the action of Coriolis force is the primary contributor to divergent- rotational KE conversion for all categories of stationary and transient waves at both the levels over tropics. In the transient synoptic scale dynamics wave-wave interaction plays a dominant role in the lower troposphere. The nonlinear KE conversion terms due to the action of different forcings are stronger at 200 hPa compared to those at 850 hPa. The divergence plays primary role for maintenance of stationary rotational; planetary scale waves as due to this effect they receive maximum amount of energy from divergent planetary flows by zonal-wave interaction at 200 hPa. Wave-wave interaction due to the action of Coriolis force transfer maximum amount of KE from divergent transient synoptic scale waves to rotational transient synoptic scale waves at 200 hPa. For stationary planetary scale waves, zonal-wave and wave-wave interactions due to the effect of vorticity are equally important for large positive divergent-rotational energy transfer at 200 hPa. In general the wave-wave KE exchanges from divergent to rotational component due to Coriolis force effect is the most dominating process for all categories of transient waves at both the levels.

Almost all the time series of rotational and divergent KE for different wave categories of combined and transient waves exhibit primary peak during the first week of July and a relatively weak secondary peak during the last week of July. These periods coincide with the period of strong monsoon depression and perhaps less intense tropical depression respectively. It is found that transient motion is dominated by synoptic scale eddies which are embedded in monsoon circulation at different phases of monsoon during July 1979. It is perhaps that over tropics at 200 hPa horizontal divergence is large during the period of monsoon depression and revival of monsoon which makes the conversion due to divergence term more significant than that due to vorticity term for combined waves. The interaction terms of energy conversion are found to be one order less in the lower troposphere compared to those in the upper troposphere. Divergence and vorticity are equally important for nonlinear energy conversion of transient waves at 850 and 200 hPa.

The results support that the energy conversion phenomenon may not be entirely barotropic. It is further concluded that nonlinear energy conversions due to Coriolis force and vorticity oppose each other at 200 hPa. Chen and Wiin-Nielsen (1976) showed that conversion between divergent and rotational KE can take place in a quasi-geostrophic model only due to Coriolis effect term. However, the present results show that contributions due to vorticity and divergence effects are also appreciable at different stages of upper tropospheric stationary planetary scale monsoon activities which indicate the importance of ageostrophic effect over tropics.

Appendix A

List of symbols

λ	longitude
ϕ	latitude, $\mu = \sin\phi$, $\mu_1 = \sin\phi_1$, $\mu_2 = \sin\phi_2$
ζ	vorticity
D	divergence
f	Coriolis parameter
ψ	stream function
χ	velocity potential
$\nabla\chi$	grad of χ
$u2$, $v2$	zonal and meridional components of rotational wind $v2$
$u3$, $v3$	zonal and meridional components of divergent wind $v3$
$x2(n, 1)$, $x2(n,2)$	Fourier cosine and sine coefficients of rotational field $x2$ for wave n respectively
$x3(n, 1)$, $x3(n, 2)$	Fourier cosine and sine coefficients of divergent field $x3$ for wave n respectively
$\overline{X} = \frac{1}{2\pi}\int_0^{2\pi} X\, d\lambda$	zonal average of X
$X' = X - \overline{X}$	departure from zonal average
$K2(n)$	rotational KE for wave number n
$K3(n)$	divergent KE for wave number n

Appendix B

Equations

$$K2(n) = \frac{1}{4(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \sum_{i=1}^{2} \left[\{u2(n,i)\}^2 + \{v2(n,i)\}^2 \right] d\mu$$

$$K3(n) = \frac{1}{4(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \sum_{i=1}^{2} \left[\{u3(n,i)\}^2 + \{v3(n,i)\}^2 \right] d\mu$$

$$CFWW(n) = \frac{1}{4(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} f \sum_{i=1}^{2} \{ u2(n,i)v3(n,i) - u3(n,i)v2(n,i) \} d\mu$$

$$CVZW(n) = \frac{1}{4(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \left[\overline{\zeta} \sum_{i=1}^{2} \{ u2(n,i)\, v3(n,i) - u3(n,i)v2(n,i) \} + \overline{u2} \sum_{i=1}^{2} \{ \zeta(n,i)\, v3(n,i) \} + \overline{v3} \sum_{i=1}^{2} \{ \zeta(n,i)\, u2(n,i) \} \right] d\mu$$

$$CVWW(n) = \frac{1}{4(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \sum_{i=1}^{2} \zeta(n,i)\, C\zeta(n,i)\, d\mu$$

$$CDZW(n) = -\frac{1}{8(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \left[\overline{D} \sum_{i=1}^{2} \{ u2(n,i)u2(n,i) + v2(n,i)v2(n,i) \} + \overline{u2} \sum_{i=1}^{2} \{ D(n,i)\, u2(n,i) + D(n,i)u2(n,i) \} \right] d\mu$$

$$CDWW(n) = -\frac{1}{8(\mu_2 - \mu_1)} \int_{\mu_1}^{\mu_2} \left[\sum_{i=1}^{2} D(n,i)CD(n,i) \right] d\mu$$

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

$$C\zeta = u2' \, v3' - u3' \, v2'$$

$$CD = u2' \, u2' + v2' \, v2'$$

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