

Role of atmospheric wave interaction in the generation of easterly zonal current in the monsoon region

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संक्षेप — ग्रीष्म में मानसून परिसंचन का एक महत्वपूर्ण अर्धस्थायी अभिलक्षण है उष्णकटिबंधीय पूर्वी जेट (टी० ई० जे०)।

प्रस्तुत शोधपत्र में उष्णकटिबंधीय पूर्वी जेट की उत्पत्ति में उष्णकटिबंधीय क्षेत्रों में विद्यमान विभिन्न तरंगों की अन्योन्यक्रिया के योगदान का अध्ययन करने का प्रयास किया गया है। मानसून परिसंचन के महत्वपूर्ण प्रवाह प्रारूपों में से ऊर्जा विनिमय प्रक्रिया के विश्लेषण के लिए बहु-माप तकनीक का उपयोग किया गया है। हमने विभिष्टतया, अनुनाद की दशा में तरंग त्रयी के ग्यारह समुच्चयों का उपयोग किया है। उसमें यह पाया है कि उनमें से तीन उष्ण कटिबंधीय पूर्वी जेट जैसी संरचना की उत्पत्ति या उत्तेजन क्रिया में बढ़ावा देते हैं।

ABSTRACT. One of the significant semi-permanent features of the monsoon circulation of the summers is the tropical easterly jet (TEJ).

The present paper is an attempt to study the contribution from interaction amongst various waves prevalent in tropical regions towards the generation of the TEJ. The multiple scale technique has been used to analyse energy exchange process amongst the significant flow patterns of the monsoon circulation. Specifically, we have considered eleven sets of wave triads under the condition of resonance and it is noted that three of these support excitation or generation of TEJ type structure.

1. Introduction

The global aspects of monsoon form an important feature of the general circulation. Planetary scale of monsoon is largely confined to stationary wave numbers 1 to 3 with monsoon trough forming its important component. Superimposed on these are a number of waves extending from wave numbers 5 to 8, these being monsoon disturbances. The other important feature of summer monsoon circulation on the upper troposphere is the existence of Tropical Easterly Jet, popularly denoted as 'TEJ'.

During the summers a well developed easterly jet is normally observed over India and north Africa. These strong easterly winds flow south of the subtropical ridge, are a characteristic feature of Asia and Africa during the summers and are not observed elsewhere over the globe. These are generally found to originate from the region near southeast China Sea, and accelerate to the maximum intensity near 13 deg. N and 80 deg. E. Thereafter, they decelerate over the western coast of Africa. The TEJ reaches its greatest intensity near 100-150 mb level. It may be noted that this is a mean condition; on individual days there

are differences in the location of the maxima. The TEJ was studied in details by Koteswaram (1958). According to him, the first burst of the monsoon coincides with the establishment of the TEJ over south India. He also showed the relationship between the precipitation distribution and the location of the axis of the TEJ.

The generation of the TEJ is closely associated with the Tibetan plateau which is a vast land mass situated at a height of about 6 km and acts as an elevated heat source (Koteswaram 1958; Reiter 1961). Consequently, a quasi-stationary anticyclone establishes over the Tibetan plateau. In association with mid-latitude westerly trough, air flows to the south along the eastern edge of this anticyclone and carries the easterly momentum. This has been considered, to a great extent, as the primary mechanism for the generation of the TEJ. Nevertheless, the origin of the TEJ is still not well understood and therefore the relevant tropical atmospheric phenomena are required to be observed and studied closely.

Among the observed features of the general circulation are wave like motions and theoretical investigations

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reveal that the tropical energy source mechanisms tend to act more efficiently upon certain wave types over preferred length scales. The essence of the theoretical investigation by Kuo (1975) who studied the CISK mechanism, and observational evidence furnished by Kanamitsu *et al.* (1972) of wave-wave and wave-zonal interactions using a spectral method of analysis, have shown the existence of finite amplitude tropical waves which play an important role in the atmospheric dynamics. Kanamitsu *et al.* (1972) also showed that the wave numbers 1 and 3 feed energy to the zonal flow. The aim of the present paper is to investigate the redistribution of the energy in the tropical region due to the nonlinear interaction among the atmospheric waves. Das *et al.* (1981), extending the formulation of Matsuno (1966), Duffy (1974), studied the resonance between wave triads composed of (a) Rossby waves (b) Rossby-gravity waves (c) Eastward moving inertia gravity waves (d) nondispersive Kelvin wave and zonal current. In the present study, we have utilised same model as above and have carried out an analysis similar to Domaracki *et al.* (1977) and Loesch (1977). The multiple scale technique is used to analyse the energy exchange processes amongst the significant flow pattern of monsoon circulation.

While we realize that the special physiographic and thermodynamic features play an important role in the formation of the TEJ, we will study here the extent to which interacting atmospheric waves in the monsoon region can contribute towards the excitation of the easterly jet. Specifically, we ask: "Can suitable triads be considered which could, as a result of resonance, support generation of the upper tropospheric easterly jet"?

2. The model

The model is a shallow water model of constant depth H . The fluid is assumed to be inviscid, homogeneous and hydrostatic. We will make use of an equatorial infinite β -plane which means that

$$f \simeq \beta y, \quad \beta = \left(\frac{df}{dy} \right)_y = 0$$

where, y is the meridional distance from the equator. The dynamical system in local Cartesian frame of reference in non-dimensional form is given as

$$u_t + \epsilon (uu_x + vu_y) - yv + \phi_x = 0 \quad (1a)$$

$$v_t + \epsilon (uv_x + vv_y) + yu + \phi_y = 0 \quad (1b)$$

$$\phi_t + \epsilon [(u\phi)_x + (v\phi)_y] + u_x + v_y = 0 \quad (1c)$$

where, the symbols have their usual meanings and ϵ is the equatorial Rossby number defined as the ratio of the characteristic phase speed (U) of the Rossby wave, to the speed ($c = \sqrt{gH}$) of the shallow water gravity waves in the equatorial region. The characteristic features of the physical model are incorporated by referring the horizontal coordinates (x and y) to the length scale

$L = \sqrt{c/\beta}$, the time to $T = \sqrt{1/(\beta c)}$ and the geopotential $\phi (=gz)$ to cU . The horizontal velocity

components (u and v) are referred to U . Taking $U \sim 10 \text{ ms}^{-1}$, $c \sim 100 \text{ ms}^{-1}$, we find that $\epsilon \sim 0 (10^{-1})$, $L \sim 2000 \text{ km}$ and $T \sim 6 \text{ hours}$.

The model chosen here is well suited for determining the dynamics of resonance among triads composed of the same as well as different wave types occurring in the tropical region. The nonlinearity of the system implies that the superposition of the waves is not valid. Instead, the vorticity of one wave is advected by the velocity field of another and the waves are entrapped by nonlinearity to interact with one another for the energy exchange among themselves.

The problem posed above corresponds to the large cumulative effects represented by the nonlinear advective terms which can be appropriately tackled by introducing the slow variables: $T_1 = \epsilon t$, $T_2 = \epsilon^2 t$, $X_1 = \epsilon x$, $X_2 = \epsilon^2 x$ which represent the long scales (*i.e.*, planetary time and space scales). This implies that

$$\frac{\partial}{\partial x} \text{ and } \frac{\partial}{\partial t} \text{ become } \frac{\partial}{\partial x} + \epsilon \frac{\partial}{\partial X_1} + \epsilon^2 \frac{\partial}{\partial X_2} \text{ and } \frac{\partial}{\partial t} + \epsilon \frac{\partial}{\partial T_1} + \epsilon^2 \frac{\partial}{\partial T_2} \text{ respectively.}$$

Let $u(x, y, t, X_1, X_2, T_1, T_2, \epsilon) \simeq$

$$\begin{aligned} & u^{(0)}(x, y, t, X_1, X_2, T_1, T_2) + \\ & + \epsilon u^{(1)}(x, y, t, X_1, X_2, T_1, T_2) + \dots \end{aligned} \quad (2)$$

with similar expansions for v and ϕ .

Substituting in (1), the method of asymptotic technique then leads to system of order 1, ϵ , ϵ^2 , ... equations which are solved by applying the condition that the secular terms are avoided,

0(1) Problem

The system is

$$u_t^{(0)} - yv^{(0)} + \phi_x^{(0)} = 0 \quad (3a)$$

$$v_t^{(0)} + yu^{(0)} + \phi_y^{(0)} = 0 \quad (3b)$$

$$\phi_t^{(0)} + u_x^{(0)} + v_y^{(0)} = 0 \quad (3c)$$

as treated by Matsuno (1966) in detail, its solution is

$$u^{(0)} = \sum_{n=0}^{\infty} \sum_{j=1}^3 \left\{ -\frac{1}{2} (\sigma_j + k_j) \psi_{n+1} - n (\sigma_j - k_j) \psi_{n-1} \right\} C_{jn}(X, T) e^{i(k_j x - \sigma_j t)} + \dots \quad (4a)$$

$$v^{(0)} = \sum_{n=0}^{\infty} \sum_{j=1}^3 i (\sigma_j^2 - k_j^2) \psi_n C_{jn}(X, T) e^{i(k_j x - \sigma_j t)} + \dots \quad (4b)$$

$$\phi^{(0)} = \sum_{n=0}^{\infty} \sum_{j=1}^3 \left\{ -\frac{1}{2} (\sigma_j + k_j) \psi_{n+1} + n (\sigma_j - k_j) \psi_{n-1} \right\}$$

$$C_{jn}(X, T) e^{i(k_j x - \sigma_j t)} + ** \quad (4c)$$

under the dispersion constraints

$$\sigma_j^2 - k_j^2 - k_j/\sigma_j = 2n + 1, \quad n = 0, 1, 2, \dots$$

$$j = 1, 2, 3, \dots$$

with $\psi_n = e^{-y^2/2} H_n(y)$ named as Weber's Hermite polynomial of degree n . Asterisk(*) denotes complex conjugate.

0 (e) Problem

This is governed by the system

$$u_t^{(1)} - yv^{(1)} + \phi_x^{(1)} = -u_{T_1}^{(0)} - \phi_{X_1}^{(0)} - u^{(0)} u_x^{(0)} - v^{(0)} u_y^{(0)} \quad (5a)$$

$$v_t^{(1)} + yu^{(1)} + \phi_y^{(1)} = -v_{T_1}^{(0)} - u^{(0)} v_x^{(0)} - v^{(0)} v_y^{(0)} \quad (5b)$$

$$\phi_t^{(1)} + u_x^{(1)} + v_y^{(1)} = -\phi_{T_1}^{(0)} - u_{X_1}^{(0)} - (u^{(0)} \phi^{(0)})_x - (v^{(0)} \phi^{(0)})_y \quad (5c)$$

With its homogeneous part identical to 0(1) system.

Elimination of $u^{(1)}$ and $\phi^{(1)}$ among Eqns. 5(a) to 5(c) reduces the system to the equation

$$v_{yyt}^{(1)} - y^2 v_t^{(1)} - v_{utt}^{(1)} + v_{xxt}^{(1)} + v_x^{(1)}$$

$$= 3 v_{uT_1}^{(0)} + y^2 v_{T_1}^{(0)} - v_{yyT_1}^{(0)} - v_{xxT_1}^{(0)} - v_{X_1}^{(0)}$$

$$- 2 v_{xtX_1}^{(0)} + (u v_x^{(0)})_t + (v v_y^{(0)})_t - (u v_x^{(0)})_{xx}$$

$$- (v v_y^{(0)})_{xx} - y(u u_x^{(0)})_t - y(v u_y^{(0)})_t +$$

$$+ y(u \phi_x^{(0)})_x + y(v \phi_y^{(0)})_x - (u \phi_x^{(0)})_{yt}$$

$$- (\phi u_x^{(0)})_{yt} - (v \phi_y^{(0)})_{yt} - (v_y \phi^{(0)})_{yt} +$$

$$+ (u_x u_x^{(0)})_{xy} + (v u_y^{(0)})_{xy} + y(u_x \phi^{(0)})_x +$$

$$+ y(v \phi_y^{(0)})_x \quad (6)$$

The Eqn. (6) under orthogonality restriction

$$\text{Lt. } \frac{1}{2x\tau} \int_{-\infty}^x \int_{-\infty}^{\infty} \int_0^{\tau} v_b^{(1)} \times [(\text{Inhomogeneities})] \quad (7)$$

of Eqn. (6)] $dx dy dt = 0$ with $v_b^{(1)}$ is a harmonic of general homogeneous solution to (6) and resonance conditions.

$$\sum_{j=1}^3 \sigma_j = 0 \quad (8a)$$

$$\sum_{j=1}^3 k_j = 0 \quad (8b)$$

$$\sum_{j=1}^3 n_j \text{ odd} \quad (8c)$$

as discussed by Domaracki and Loesch (1977) yields the solution to the system (5) as

$$v^{(1)} = \hat{v}^{(1)} + \sum_{1,2,3} \left[E_1^{(1)} C_{2n}^* C_{3n}^* + E_1^{(2)} i C_{1nT_1} + E_1^{(3)} i C_{1nX_1} \right] \frac{e^{i\theta_1}}{i\sigma_1} + \text{Terms involving}$$

arguments of the form $(\theta_r - \theta_s)$ and $2\theta_r + **$ (9a)

$$u^{(1)} = \hat{u}^{(1)} + \sum_{1,2,3} \left[G_1^{(1)} C_{2n}^* C_{3n}^* +$$

$$+ G_1^{(2)} i C_{1nT_1} + G_1^{(3)} i C_{1nX_1} \right] \frac{e^{i\theta_1}}{(-\sigma_1^2 + k_1^2)} +$$

+ Terms involving arguments of the form $(\theta_r - \theta_s)$ and $2\theta_r + **$ (9b)

$$\phi^{(1)} = \hat{\phi}^{(1)} + (-v_y^{(1)})_t + \sum_{1,2,3} (S_1^{(1)} C_{2n}^* C_{3n}^* + S_1^{(2)} i C_{1nT_1} + S_1^{(3)} i C_{1nX_1}) e^{i\theta_1} +$$

terms involving the arguments of the form $\theta_r - \theta_s$ and $2\theta_r + **$ (9c)

where,

E_s, G_s and S_s are referred to the Appendix (1)

$$\theta_j = k_j x - \sigma_j t \quad (j = 1, 2, 3)$$

and $\hat{u}^{(1)}, \hat{v}^{(1)}, \hat{\phi}^{(1)}$ are functions of $y, X_1, X_2, \dots, T_1, T_2, \dots$ each, assumed to exist and to be determined from 0(ϵ^2) system of equations associated with problem

(1). This can be achieved by equating identically the x and t independent nonoscillatory parts from the $O(\epsilon^2)$ system which arise from the interactions under resonance between free mode and forced modes on the right hand side of equations in $O(\epsilon^2)$ system. The other parts of $v^{(1)}$ are the solutions corresponding to the inhomogeneities in Eqn. (6) and those $u^{(1)}$ and $\phi^{(1)}$ are determined from the solution $v^{(1)}$ and little algebra of elimination among (5).

$O(\epsilon^2)$ System

The $O(\epsilon^2)$ system associated with (1) is

$$\begin{aligned} u_t^{(2)} - yv^{(2)} + \phi_x^{(2)} &= -u_{T_1}^{(1)} - \phi_{X_1}^{(1)} \\ &- (u^{(0)}u_x^{(1)} + u^{(1)}u_x^{(0)}) - u_{T_2}^{(0)} \\ &- (\phi_{X_2}^{(0)} - u^{(0)}u_{X_1}^{(0)} - (v^{(0)}u_y^{(1)} + \\ &+ v^{(1)}u_y^{(0)})) \end{aligned} \quad (10a)$$

$$\begin{aligned} v_t^{(2)} + yu^{(2)} + \phi_y^{(2)} &= -v_{T_1}^{(1)} - v_{T_2}^{(0)} \\ &- (u^{(0)}v_x^{(1)} + u^{(1)}v_x^{(0)}) - u^{(0)}v_{X_1}^{(0)} \\ &- (v^{(0)}v_y^{(1)} + v^{(1)}v_y^{(0)}) \end{aligned} \quad (10b)$$

$$\begin{aligned} \phi_t^{(2)} + u_x^{(2)} + v_y^{(2)} &= -\phi_{T_1}^{(1)} - \phi_{T_2}^{(0)} \\ &- u_{X_1}^{(1)} - u_{X_2}^{(0)} - (u^{(0)}\phi^{(1)} + \\ &+ u^{(1)}\phi^{(0)})_x - (u^{(0)}\phi^{(0)})_{X_1} - (v^{(0)}\phi^{(1)} + \\ &+ v^{(1)}\phi^{(0)})_y \end{aligned} \quad (10c)$$

On equating the nonoscillatory parts from the Eqns. 10(a) and 10(c) one can be led to the equations

$$\begin{aligned} -y\hat{v}^{(2)} + \hat{u}_{T_1}^{(1)} + \hat{\phi}_{X_1}^{(1)} &= |C_{1n}|^2_{T_1} W_1 + \\ &+ |C_{2n}|^2_{T_1} W_2 + |C_{3n}|^2_{T_1} W_3 + \\ &+ |C_{1n}|^2_{X_1} W_4 + |C_{2n}|^2_{X_1} W_5 + \\ &+ |C_{3n}|^2_{X_1} W_6 \end{aligned} \quad (11a)$$

$$\begin{aligned} \hat{v}_y^{(2)} + \hat{u}_{X_1}^{(1)} + \hat{\phi}_{T_1}^{(1)} &= |C_{1n}|^2_{T_1} W_7 + \\ &+ |C_{2n}|^2_{T_1} W_8 + |C_{3n}|^2_{T_1} W_9 + \\ &+ |C_{1n}|^2_{X_1} W_{10} + |C_{2n}|^2_{X_1} W_{11} + \\ &+ |C_{3n}|^2_{X_1} W_{12} \end{aligned} \quad (11b)$$

where $\hat{v}^{(2)}$ is nonoscillatory part of $v^{(2)}$ and W_1 through W_{12} are various coefficient functions of y . Useful coefficients are given in the Appendix (1). The system (11) with the system

$$y\hat{u}^{(1)} + \hat{\phi}_y^{(1)} = |C_{1n}|^2 W_{13} + |C_{2n}|^2 W_{14} + |C_{3n}|^2 W_{15} \quad (12a)$$

$$\hat{v}^{(1)} = 0 \quad (12b)$$

which is necessary for the validity of existence of $\hat{u}^{(1)}$, $\hat{v}^{(1)}$, $\hat{\phi}^{(1)}$ and deduced from the system (5) constitutes the closed system for the unknown variables $\hat{u}^{(1)}$, $\hat{\phi}^{(1)}$ and $\hat{v}^{(2)}$.

W_s are referred to the Appendix (1).

The system (1) and (12) provide the zonal flow on temporal and spatial scales which are filtered out under following two case studies.

3. Case studies

3.1. Case study (1)

When wave triads remain discrete all along, *i.e.*, their amplitudes are independent of X_1 , the zonal Eqn. (11) reduces to

$$-y\hat{v}^{(2)} + \hat{u}_{T_1}^{(1)} = \sum_{j=1}^3 |C_{jn}|^2_{T_1} W_j \quad (13a)$$

$$\begin{aligned} \hat{v}_y^{(2)} + \hat{\phi}_{T_1}^{(1)} &= |C_{1n}|^2_{T_1} W_7 + |C_{2n}|^2_{T_1} W_8 + \\ &+ |C_{3n}|^2_{T_1} W_9 \end{aligned} \quad (13b)$$

The algebraic eliminations among systems (13) and (12a) impart

$$\hat{u}_{T_1}^{(1)} = |C_{jn}|^2_{T_1} W_j + y\hat{v}^{(2)} \quad (14)$$

with

$$\begin{aligned} \hat{v}_{yy}^{(2)} - y^2\hat{v}^{(2)} &= |C_{1n}|^2_{T_1} (yW_1 + W'_7 - W_{13}) + \\ &+ |C_{2n}|^2_{T_1} (yW_2 + W'_8 - W_{14}) + \\ &+ |C_{3n}|^2_{T_1} (yW_3 + W'_9 - W_{15}) \end{aligned} \quad (15)$$

The careful examination of the operator on $\hat{v}^{(2)}$ in Eqn. (15) exhibits no prolific solution to (15) as it remains unbounded throughout. This suggests the wave interaction as no cause of the generation of zonal current on the time scale T_1 . This is also confirmed numerically (results not presented). The dash (') above and henceforth stands for differentiation with respect to y .

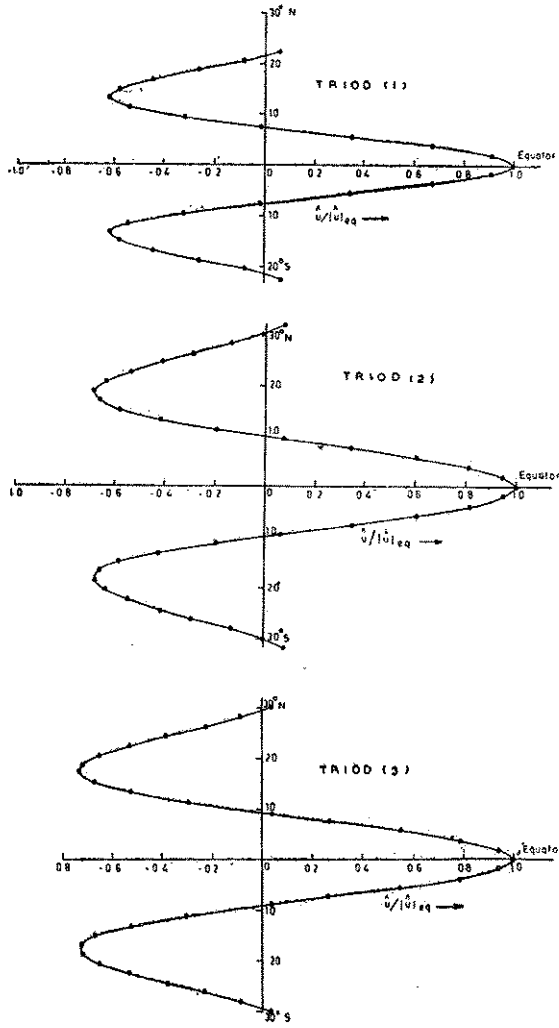


Fig. 1. Zonal flow profile generated by the triad(1), triad(2) & triad(3)

3.2. Case study (2)

The continuity of wave spectra and invariance of amplitudes of the interacting waves on temporal scale T_1 reduce the system (11) to

$$-y\hat{v}^{(2)} + \hat{\phi}_{X_1}^{(1)} = |C_{1n}|^2_{X_1} W_4 + |C_{2n}|^2_{X_1} W_5 + |C_{3n}|^2_{X_1} W_6 \quad (16a)$$

$$\hat{v}_y^{(2)} + \hat{u}_{X_1}^{(1)} = |C_{1n}|^2_{X_1} W_{10} + |C_{2n}|^2_{X_1} W_{11} + |C_{3n}|^2_{X_1} W_{12} \quad (16b)$$

The algebraic elimination among systems (16) and equations 12(a) yields

$$\begin{aligned} \hat{u}_{X_1} = & |C_{1n}|^2_{X_1} (W_4'' + yW'_{10} + 2W_{10} - W'_{12}) + \\ & + |C_{2n}|^2_{X_1} (W_5'' + yW'_{11} + 2W_{11} - W'_{14}) + \\ & + |C_{3n}|^2_{X_1} (W_6'' + yW'_{12} + 2W_{12} - W'_{15}) \end{aligned} \quad (17)$$

As previously mentioned, the orthogonality condition bears the well known amplitude relations

$$I_1^{(1)} C_{2n}^* C_{3n}^* + I_1^{(3)} i C_{1n} X_1 = 0 \quad (18a)$$

$$I_2^{(1)} C_{3n}^* C_{1n}^* + I_2^{(3)} i C_{2n} X_1 = 0 \quad (18b)$$

$$I_3^{(1)} C_{1n}^* C_{2n}^* + I_3^{(3)} i C_{3n} X_1 = 0 \quad (18c)$$

whereunder Eqn. (17) yields zonal flow \hat{u} as

$$\begin{aligned} \hat{u} = & (|C_{1n}|^2 - |C_{1n}|^2_{(X_1=0)}) \left\{ (W_4'' + yW'_{10} + \right. \\ & + 2W_{10} - W'_{12}) + \frac{I_1^{(3)} I_2^{(1)}}{I_1^{(1)} I_2^{(3)}} (W_5'' + yW'_{11} + \\ & + 2W_{11} - W'_{14}) + \frac{I_1^{(3)} I_3^{(1)}}{I_1^{(1)} I_3^{(3)}} (W_6'' + yW'_{12} + \\ & \left. + 2W'_{12} - W'_{15}) \right\} \end{aligned}$$

and the symbols $I_j^{(1)}$ signifying as

$$\begin{aligned} I_j^{(1)} &= \int_{-\infty}^{\infty} F_j^{(1)} v_j^{(0)} dy \\ I_j^{(3)} &= \int_{-\infty}^{\infty} F_j^{(3)} v_j^{(0)} dy \end{aligned} \quad (19)$$

The profiles of the solution relative to the magnitude of the current at equator were computed for various triads presented in Table 1. Out of them, the profiles with respect to first three triads are very interesting and have been presented in Fig. 1.

3.2.1. The critical examinations of various profiles for the 11 triads studied (only 3 presented) lead us to the observations presented in Table 1.

4. A physical interpretation of the results

In nature we observe two categories of easterly jets. One jet system is of synoptic scale and its location and period of existence is of sporadic nature. Such a system can occur anywhere on the globe at the southern periphery of an anticyclone. Detailed study of one such case

TABLE 1
 Characteristics of zonal profiles generated by different wave triads

Triad No.	Wave type	Characteristic values			Generated zonal profile's features observed		
		k_j	σ_j	n_j	Physical properties	Nature of equatorial jet	Nature of side jets and location of side wind maxima
1	Rossby	1.1631	-0.1395	3	Very uniform, smooth with some sort of sinusoidal character along a meridian, symmetry about-equator.	Westerly	easterly, around 13°N and S, <i>i.e.</i> , a region very close to the location of TEJ
	Rossby	-2.3262	0.2791	1			
	Rossby	1.1631	-0.1395	3			
2	Rossby	-1.6563	0.2927	1	Do.	Westerly	easterly, around 18°N and S
	Rossby	0.4932	-0.1531	1			
	Rossby	1.1631	-0.1395	3			
3	Rossby	-2.2273	0.2826	1	Do.	Westerly	Do.
	(-) I-G	0.7273	-2.2826	2			
	(+) I-G	1.5000	2.0000	0			
4	Rossby	-1.5194	0.2091	2	Do.	Easterly	westerly, around 13°N and S
	Rossby	0.3563	-0.0695	2			
	Rossby	1.1631	-0.1395	3			
5	Rossby	-1.4123	0.2031	2	No smooth general flow pattern, symmetry about equator	Easterly	Westerly, around 18°N and S
	Mixed	2.5754	-0.3426	0			
	Rossby	-1.1631	0.1395	3			
6	(+) I-G	-1.5193	-2.4356	1	Central jet less intensive with side jets of no general flow pattern, symmetry about equator.	Easterly	Westerly, around 18°N and S
	Rossby	1.1193	-0.2677	1			
	+ I-G	0.4000	2.7033	3			
7	Mixed	2.0796	-0.4028	0	Central jet of fine shape with much less intensive side jets, symmetry about equator.	Easterly	westerly, around 13°N and S
	(-) I-G	-2.1796	2.6310	1			
	(-) I-G	0.1000	-2.2282	2			
8	Mixed	0.4926	-0.7835	0	Laterally magnified and relatively less intensive jet with nonuniform side jets symmetry about equator.	Easterly	less marked
	(-) I-G	-0.5920	1.7348	1			
	Mixed	0.1000	-0.9512	0			
9	(+) I-G	-2.5652	-3.7761	3	Non-uniform, laterally magnified and much less intensive jet like flow pattern, symmetry about equator.	Westerly	No side Jets
	(+) I-G	2.1652	2.5563	0			
	(+) I-G	0.4000	1.2198	0			
10	(+) I-G	1.8449	2.2829	0	Finely shaped less intensive central jet, symmetry about equator.	Easterly	No side jets
	(+) I-G	-1.5562	-3.1490	3			
	Mixed	-0.2886	0.8660	0			
11	(-) I-G	-0.5773	1.7320	1	Less intensive central jet of wide aperture, symmetry about equator.	Easterly	less marked
	Mixed	0.2886	-0.8660	0			
	Mixed	0.2886	-0.8660	0			

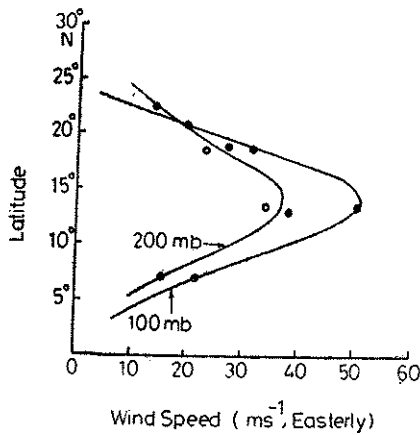


Fig. 2. Meridional profile of the east component at 100 mb and 200 mb using combined data from India and Thailand for 25 July 1955 (after Koteswaram 1958)

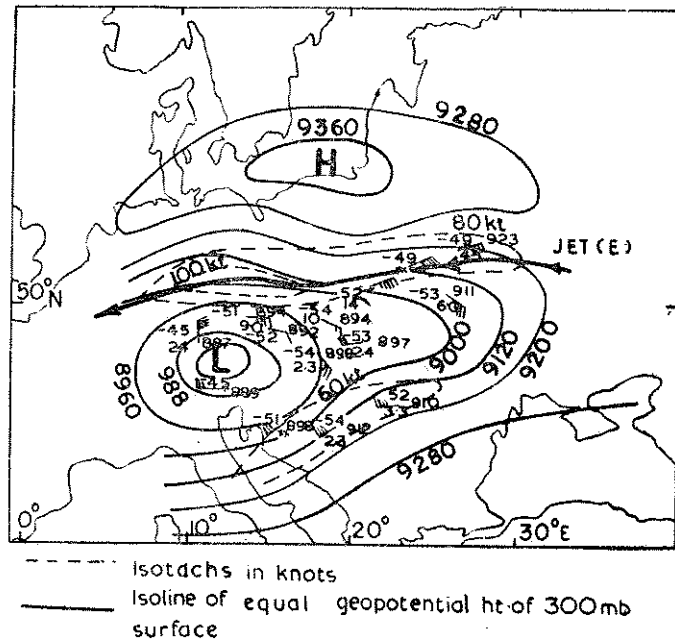


Fig. 3. Flow pattern of 300 mb level at 0000 GMT on 3 November 1980

was done by Alaka (1958). Such a feature is often observed in association with the establishment of a block. A recently observed easterly jet (in reference to the formation of the block) on 3 November 1980 at 300 mb is presented in Fig. 3. Such jet streams, being of sporadic nature, having a life time of a few days with fluctuating locations can occur anywhere and cancel out (in the mean), hence, are not reflected in the mean monthly flow pattern.

The second jet system is the TEJ which flows approximately in the same region with good order of steadiness throughout the summer monsoon season. Compared to the former system, which is sporadic in nature this jet system is quasi-stationary in nature and is well reflected in the seasonal mean flow pattern.

In both types of these jet streams, the mechanism by which they draw their momentum is as a consequence of interruption of an anticyclone when the westerly jet of temperate/subtropical zone splits and one branch travels along the periphery of the anticyclone. In the case of a synoptic scale jet stream the anticyclone is dynamic and fluctuating, whereas, in the case of the TEJ, the anticyclone is of quasi-stationary nature owing to the special characteristics of the land-sea distribution and the topography. The TEJ is thus not only observed on day-to-day basis with its fluctuation, but is prominent in mean conditions also. It would be interesting to compare the results in our two case studies with the two observed easterly jet streams.

Synoptic scale jet stream observed by Alaka (1958) are independent of space, *i.e.*, sporadic in nature and hence, are not found on mean charts. They should be compared with our case study 1, which corresponds to the interactions of triads under space independence

(on planetary scale) and does not support the excitation of the jet system in mean.

In the case study II, the wave-wave interaction has been considered under the condition of independence of temporal scale T , but dependence on space scale X . The solution under these conditions provides zonal wind profiles which have a close similarity with the observed profile of the quasi-stationary jet stream TEJ, with easterly wind maxima near $15^\circ N$ [two points of apparent dissimilarities may be noted here; (1) existence of similar structure in the southern hemisphere and (2) existence of westerly flow over and near the equator. The profile in the southern hemisphere has, for simplicity, been generated from the consideration of symmetry around the equator, and hence, may not be strictly valid. Regarding the second point, zonal westerlies were used as the initial conditions at the equator which may not be true for the region $20^\circ W$ to $140^\circ E$ but can be justified if one considers the global belt. From the observed cross-section of zonal average \bar{u} as presented by various authors (Oort and Rasmusson 1971, Newell 1972) it can be seen that the upper tropospheric flow in the tropical belt $10^\circ S$ - $20^\circ N$ during the northern summer is easterly].

Thus, the close resemblance of the structure and location of the maxima near $15^\circ N$ to the actual observed pattern of the TEJ (refer to the Fig. 2. reproduced from Koteswaram 1958) may lead one to postulate that wave-wave interaction does provide significant contribution to the generation of the TEJ.

We realise that the wave-wave interaction does not play a primary role for the generation of the TEJ : otherwise jet streams similar to the TEJ should have been observed all over the tropical belt. There are, in

fact, significant physiographic and thermodynamic features which play an important role in the generation of the TEJ. Nevertheless, the role of wave-wave interaction is note worthy and interesting.

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Appendix 1

$$W_4 = \frac{I_1^{(3)}}{3I_1^{(1)}} W + \frac{v_1^{(0)} G_1^{(3)}}{(-\sigma_1^2 + k_1^2)} - \frac{u_{1y}^{(0)} E_1^{(3)}}{\sigma_1} - (u_1^{(0)})^2$$

$$W_5 = \frac{I_2^{(3)}}{3I_2^{(1)}} W + \frac{v_2^{(0)} G_2^{(3)}}{(-\sigma_2^2 + k_2^2)} - \frac{u_{2y}^{(0)} E_2^{(3)}}{\sigma_2} - (u_2^{(0)})^2$$

$$W_6 = \frac{I_3^{(3)}}{3I_3^{(1)}} W + \frac{v_3^{(0)} G_3^{(3)}}{(-\sigma_3^2 + k_3^2)} - \frac{u_{3y}^{(0)} E_3^{(3)}}{\sigma_3} - (u_3^{(0)})^2$$

$$W_{10} = - \frac{I_1^{(3)}}{3I_1^{(1)}} Z + \frac{\phi_1^{(0)}}{\sigma_1} + E_1^{(3)} + v_1^{(0)} S_1^{(3)} + 2u_1^{(0)} \phi_1^{(0)}$$

$$W_{11} = - \frac{I_2^{(3)}}{3I_2^{(1)}} Z + \frac{\phi_2^{(0)}}{\sigma_2} + E_2^{(3)} + v_2^{(0)} S_2^{(3)} + 2u_2^{(0)} \phi_2^{(0)}$$

$$W_{12} = - \frac{I_3^{(3)}}{3I_3^{(1)}} Z + \frac{\phi_3^{(0)}}{\sigma_3} + E_3^{(3)} + v_3^{(0)} S_3^{(3)} + 2u_3^{(0)} \phi_3^{(0)}$$

$$W_{13} = - 2u_1^{(0)} v_1^{(0)} k_1 - 2v_{1y}^{(0)} v_1^{(0)}$$

$$W_{14} = - 2u_2^{(0)} v_2^{(0)} k_2 - 2v_{2y}^{(0)} v_2^{(0)}$$

$$W_{15} = - 2u_3^{(0)} v_3^{(0)} k_3 - 2v_{3y}^{(0)} v_3^{(0)}$$

$$W = \sum_{j=1}^3 \frac{u_j v^{(0)}}{\sigma_j} E_j^{(1)}, \quad Z = \sum_{j=1}^3 \left(v_j^{(0)} S_j^{(1)} + \frac{\phi_j^{(0)} E_j^{(1)}}{\sigma_j} \right)_y$$

$$\left(\frac{d^2}{dy^2} + 2n_j + 1 - y^2 \right) E_j^{(i)} = F_j^{(i)} \quad (i, j = 1, 2, 3)$$

$$S_1^{(1)} = \frac{k_1 G_1^{(1)}}{\sigma_1 (-\sigma_1^2 + k_1^2)} - \frac{1}{\sigma_1^2} E_{1y}^{(1)} - \frac{1}{\sigma_1} \left[k_1 u_2^{(0)} \phi_3^{(0)} + k_1 u_3^{(0)} \phi_2^{(0)} + \right. \\ \left. + (v_2^{(0)} \phi_3^{(0)})_y + (v_3^{(0)} \phi_2^{(0)})_y \right]$$

$$S_2^{(1)} = \frac{k_2 G_2^{(1)}}{\sigma_2 (-\sigma_2^2 + k_2^2)} - \frac{1}{\sigma_2^2} E_{2y}^{(1)} - \frac{1}{\sigma_2} \left[k_2 u_3^{(0)} \phi_1^{(0)} + k_2 u_1^{(0)} \phi_3^{(0)} + \right. \\ \left. + (v_3^{(0)} \phi_1^{(0)})_y + (v_1^{(0)} \phi_3^{(0)})_y \right]$$

$$S_3^{(1)} = \frac{k_3 G_3^{(1)}}{\sigma_3 (-\sigma_3^2 + k_3^2)} - \frac{1}{\sigma_3^2} E_{3y}^{(1)} - \frac{1}{\sigma_3} \left[k_3 u_1^{(0)} \phi_2^{(0)} \right. \\ \left. + k_3 u_2^{(0)} \phi_1^{(0)} + (v_1^{(0)} \phi_2^{(0)})_y + (v_2^{(0)} \phi_1^{(0)})_y \right]$$

$$S_j^{(2)} = \frac{k_j}{\sigma_j} \frac{G_j^{(2)}}{(-\sigma_j^2 + k_j^2)} - \frac{1}{\sigma_j^2} E_{jy}^{(2)} - \frac{1}{\sigma_j} u_j^{(0)} \quad (j = 1, 2, 3)$$

$$S_j^{(2)} = \frac{k_j}{\sigma_j} \frac{G_j^{(2)}}{(-\sigma_j^2 + k_j^2)} - \frac{E_{jy}^{(2)}}{\sigma_j^2}$$

$$F_1^{(1)} = (k_1^2 - \sigma_1^2) (-k_3 u_3^{(0)} v_2^{(0)} - k_2 u_2^{(0)} v_3^{(0)} + v_{2y}^{(0)} v_3^{(0)} + v_{3y}^{(0)} v_2^{(0)}) \\ - \left(\sigma_1 \frac{d}{dy} + k_{1y} \right) (k_1 u_2^{(0)} \phi_3^{(0)} + k_1 u_3^{(0)} \phi_2^{(0)} + (v_2^{(0)} \phi_3^{(0)})_y \\ + (v_3^{(0)} \phi_2^{(0)})_y) + \left(\sigma_1 y + k_1 \frac{d}{dy} \right) (u_2^{(0)} u_3^{(0)} k_1 + u_{2y}^{(0)} v_3^{(0)} + u_{3y}^{(0)} v_2^{(0)})$$

$$F_1^{(2)} = - \left(\sigma_1 \frac{d}{dy} + k_1 y \right) u_1^{(0)} + \left(\sigma_1 y + k_1 \frac{d}{dy} \right) \phi_1^{(0)}$$

$$G_1^{(2)} = -y E_1^{(2)} + \frac{k_1}{\sigma_1} E_{1y}^{(2)} - \sigma_1 \left(u_2^{(0)} u_3^{(0)} k_1 + u_{2y}^{(0)} v_3^{(0)} \right. \\ \left. + u_{3y}^{(0)} v_2^{(0)} \right) + k_1 \left(k_1 u_2^{(0)} \phi_3^{(0)} + k_1 u_3^{(0)} \phi_2^{(0)} + (v_2^{(0)} \phi_3^{(0)})_y \right. \\ \left. + (v_3^{(0)} \phi_2^{(0)})_y \right)$$

$$G_1^{(3)} = -y E_1^{(3)} + \frac{k_1}{\sigma_1} E_{1y}^{(3)} - \sigma_1 \phi_1^{(0)} + k_1 u_1^{(0)}$$

Change the subscripts 1, 2, 3 above in cyclic order to get the remaining
($G_j^{(1)}, G_j^{(2)}$; $j = 2, 3$)

$$u_j^{(0)} = \frac{1}{2} (\sigma_j + k_j) \psi_{n_j+1} + n_j (\sigma_j - k_j) \psi_{n_j-1}$$

$$v_j^{(0)} = (\sigma_j^2 - k_j^2) \psi_{n_j}$$

$$\phi_j^{(0)} = -\frac{1}{2} (\sigma_j + k_j) \psi_{n_j+1} + n_j (\sigma_j - k_j) \psi_{n_j-1} \quad (j = 1, 2, 3.)$$