CISK, EVAPORATION-WIND FEEDBACK MECHANISM AND 30—60 DAY OSCILLATIONS IN THE TROPICAL ATMOSPHERE *

Zhao Qiang (赵 强), *Fu Zuntao* (付遵涛), *Chen Jiong* (陈 炯) and *Liu Shikuo* (刘式适)

Department of Geophysics, Peking University, Beijing 100871

Received October 8, 1996

ABSTRACT

A baroclinic semi-geostrophic model with evaporation-wind feedback mechanism (EWFM) and CISK is established, two non-dimensional parameters α and η are introduced to represent EWFM and CISK, respectively. Analytic solutions of the model system are obtained. dynamics analyses and the model atmosphere calculations further confirm that EWFM and CISK are very important physical processes in leading to the low-frequency oscillations in the tropics.

Key words: CISK (conditional instability of the second kind), EWFM (evaporation-wind feedback mechanism), LFO (low-frequency oscillation), EWFM-CISK-Rossby wave, EWFM-CISK-Kelvin wave

I. INTRODUCTION

The low-frequency oscillations (LFO) are very important phenomena in the tropics. The eastward propagation 30—50 day oscillations in the tropical atmosphere were first observed by Madden and Julian (1971; 1972), subsequent studies (Yasunari 1979; Murakami and Nakazawa 1985; Nakazawa 1986; Lau and Chan 1985) have further confirmed the existence of LFO and found that the 30—60 day oscillations of the tropical atmosphere have slowly eastward-propagating and northward-propagating characteristics, and its zonal phase speed is about 10—15 m s^{-1}, meridional phase speed is about 1—3 m s^{-1}. Its wind and temperature fields have "baroclinic" structure. The 30—60 day oscillations also have clear two-dimensional Rossby wave-train characteristics (Lau and Lau 1986), i. e. energy dispersion. Recent studies have shown that 30—60 day oscillations not only propagate eastward or northward, but also propagate westward and southward sometimes (Knutson and Weickmann 1987; Chen et al. 1988). What is the dynamical mechanism of the LFO in the tropics? How to explain those propagating characteristics of the LFO?

Based upon the wave-CISK theories of the LFO in the tropics (Hayashi 1970; Lindzen 1974; Lau and Peng 1987; Miyahara 1987; Takahashi 1987; Liu and Wang 1992; Li

* This work is supported by the National Natural Science Foundation of China.

1990) and EWFM theory (Emanuel 1987; Neelin et al. 1987), in the present paper, we will elucidate the crucial roles played by EWFM and CISK simultaneously in giving rise to the LFO, especially give certain explanation to the dynamical mechanism and the propagating characteristics.

II. BASIC EQUATIONS

Observed low frequency waves are characterized by horizontal length scales: the zonal scale ($L_x \sim 10^7$ m) is much larger than the meridional scale ($L_y \sim 10^6$ m). A scale analysis shows that the meridional acceleration in the v-momentum equation can be neglected. The zonal wind component is thus in geostrophic balance with meridional pressure gradient and the motion is semigeostrophic. So we use the following governing equations for a stably ($N^2 > 0$) stratified Boussinesq fluid including the EWFM and CISK to study the internal dynamics associated with the LFO in the atmosphere.

$$\begin{cases} \dfrac{\partial u}{\partial t} - fv = -\dfrac{\partial \Phi}{\partial x}, \\ fu = -\dfrac{\partial \Phi}{\partial y}, \\ \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = 0, \\ \dfrac{\partial}{\partial t}(\dfrac{\partial \Phi}{\partial z}) + N^2 w = N^2 \eta(z) w_B - N^2 \alpha u, \end{cases} \tag{1}$$

where N is the Brunt-Väisälä frequency assumed to be constant, Coriolis parameter $f = f_0 + \beta y$, ($\beta = \partial f / \partial y$); w_B vertical velocity at the top of the boundary layer and $\eta(z)$ means the non-dimensional parameter of latent heat which is assumed to depend only on height and non-zero only when $w_B > 0$. $N^2 \eta(z) w_B$ represents the latent heating in the CISK mechanism. $-N^2 \alpha u$ represents the perturbation evaporation. α means the non-dimensional parameter of EWFM which is assumed to be constant, and $\alpha < 0$ for mean surface westerlies ($\bar{u} > 0$) and $\alpha > 0$ for mean surface easterlies ($\bar{u} < 0$). This formulation is similar to that of Emanuel (1987) and Neelin et al. (1987) although the focus of the present analysis is quite different. Notice that the magnitude of α is independent of the mean wind but the sign of the mean is important. Therefore although we have not included the explicit effect of the mean wind in Eq. (1), its effect has been incorporated into the evaporation parameterization. Other notations are standard.

Using 2-layer model atmosphere (Fig. 1), by considering boundary conditions $w_0 = w_4 = 0$, and the general distribution characteristic of the vertical velocity, we can assume $w_B = b w_2$, and we define

$$\begin{cases} \hat{u} = \dfrac{1}{2}(u_1 - u_3), \\ \hat{v} = \dfrac{1}{2}(v_1 - v_3), \\ \hat{\Phi} = \dfrac{1}{2}(\Phi_1 - \Phi_3). \end{cases} \tag{2}$$

For simplicity, we assume $u_2 = 2\hat{u} = u_1 - u_3$, obviously u_2 is the zonal component of the thermal wind between the first layer and the third layer, thus, Eq. (1) can be rewritten as

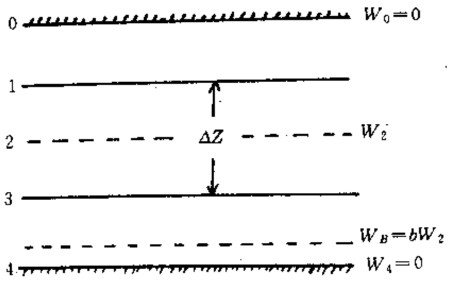

Fig. 1. Schematic vertical structure of the model atmosphere.

$$\begin{cases} \dfrac{\partial \hat{u}}{\partial t} - f\hat{v} = -\dfrac{\partial \hat{\Phi}}{\partial x}, \\ f\hat{u} = -\dfrac{\partial \hat{\Phi}}{\partial y}, \\ \dfrac{\partial \hat{\Phi}}{\partial t} + c_1^2(1 - b\eta_2)(\dfrac{\partial \hat{u}}{\partial x} + \dfrac{\partial \hat{v}}{\partial y}) = -\lambda \alpha c_1^2 \hat{u}, \end{cases} \tag{3}$$

where

$$c_1^2 = \frac{\sqrt{2}}{2} N(\Delta z), \quad \lambda = 2/\Delta z \tag{4}$$

and η_2 is the latent heating parameter on the second layer. Eliminating $\hat{\Phi}$ and $\hat{u}$ from Eq. (3) we have

$$\mathcal{L}\hat{v} = 0. \tag{5}$$

where

$$\mathcal{L} = \frac{\partial}{\partial t}\left[f^2 - c_1^2(1 - b\eta_2)\frac{\partial^2}{\partial y^2}\right] - \beta c_1^2(1 - b\eta_2)\frac{\partial}{\partial x} - \lambda \alpha c_1^2 (f\frac{\partial}{\partial y} + \beta). \tag{6}$$

Equation (5) is the basic equation which will be used to discuss the physical processes of EWFM and CISK.

III. LFO IN THE OFF-EQUATORIAL ATMOSPHERE

In this case, f=constant. Therefore, we may assume that Eq. (5) has the following wave solution,

$$\hat{v} = Ve^{i(kx+ly-\omega t)}, \tag{7}$$

where k and l are the wavenumbers in x and y directions, respectively. ω is angular frequency. Since ω is in general complex, we should have

$$\omega = \omega_r + i\omega_i. \tag{8}$$

From Eqs. (5), (7) and (8) we can obtain the disturbance frequency (ω_r) and growth rate (ω_i)

$$\omega_r = \frac{-\lambda \alpha f l - \beta k(1 - b\eta_2)}{d^2 + (1 - b\eta_2)l^2}, \tag{9}$$

$$\omega_i = \frac{\lambda \alpha \beta}{d^2 + (1 - b\eta_2)l^2}, \tag{10}$$

respectively, where $d = f/c_1$, d^{-1} is the Rossby deformation radius in the baroclinic 2-layer model atmosphere. From Eq. (9) we can also obtain the phase and group speeds as follows:

$$c_x = \frac{\omega_r}{k} = \frac{-\lambda\alpha fl/k - \beta(1-b\eta_2)}{d^2+(1-b\eta_2)l^2}, \tag{11}$$

$$c_y = \frac{\omega_r}{l} = \frac{-\lambda\alpha f - \beta k(1-b\eta_2)/l}{d^2+(1-b\eta_2)l^2}, \tag{12}$$

$$c_{gx} = \frac{\partial\omega_r}{\partial k} = -\frac{\beta(1-b\eta_2)}{d^2+(1-b\eta_2)l^2}, \tag{13}$$

$$c_{gy} = \frac{\partial\omega_r}{\partial l} = \frac{-\lambda\alpha f[d^2-(1-b\eta_2)l^2]+2\beta kl(1-b\eta_2)^2}{[d^2+(1-b\eta_2)l^2]^2}. \tag{14}$$

Obviously, the solutions to Eq. (5) are those diabatic Rossby waves which include the effects of EWFM and CISK. For convenience, we name them as the EWFM-CISK-Rossby waves. It can be seen from Eqs. (9) — (14) that these kinds of EWFM-CISK-Rossby waves are unstable and dispersive ($\omega_i \neq 0$, $c_x \neq c_{gx}$, $c_y \neq c_{gy}$), their propagating orientations depend on α and η_2. Next, based upon the physical parameters of the tropical atmosphere, the unstable growth rate (ω_i) and the phase and group speeds of the EWFM-CIFK-Rossby waves are calculated from Eqs. (9) — (14) for different conditions, so we can further investigate the properties of these kinds of waves, and compare their characteristics with the activities of the 30—60 day oscillations in the tropical atmosphere. In the end, we will point out that EWFM and CISK' s coactions are very important physical processes in triggering and driving the 30 — 60 day oscillations in the off-equatorial tropical atmosphere.

Taking $N=10^{-2}\text{s}^{-1}$, $\Delta z=5$ km, $b=0.5$, $\alpha=2.0\times10^{-4}$, $c_1\approx35.0$ m s^{-1}, $\lambda=4.0\times10^{-4}$ m^{-1}. On the other hand, the atmospheric waves are in general $L_x>L_y$. To simplify the discussions, we adopt $L_x=2L_y$ (i. e. $l=2k$). Figures 2a and 2b show c_x as a function of the latent heating and latitudes at fixed wavelength ($L_y=60000$ km); Figs. 2c and 2d show c_x as a function of the latent heating and wavenumbers at fixed latitude (25°N). It can be seen clearly that, without the latent heating or the heating being weak, all waves propagate westward ($c_x<0$), only when the heating reaches certain values can the waves propagate eastward ($c_x>0$), when the heating is stronger enough, the waves become westward-propagating again. Figure 3a shows c_{gx} as a function of the heating and latitudes at fixed wavelength ($L_y=60000$ km); Fig. 3b shows c_{gx} as a function of the heating and wavenumbers at fixed latitude (25°N). From Fig. 3 it can be seen that, with changes of the heating, the c_{gx} can be negative or positive, i. e. the waves can disperse energy westward or eastward. Since c_{gx} is independent of EWFM, if there is no EWFM, then Figs. 2a and 2b are reduced to Fig. 3a; Figs. 2c and 2d reduced to Fig. 3b. This result shows that EWFM makes the waves become weakly dispersive in the zonal direction. Figures 4a and 4b show c_y as a function of the heating and latitudes at fixed wavelength ($L_y=6000$ km); Figs. 4c and 4d show c_y as a function of the heating and wavenumbers at fixed latitude (25°N). From Fig. 4 it can be seen that without the latent heating or the heating being weak, all waves propagate southward ($c_y<0$), only when the heating reaches a certain value can the waves propagate northward ($c_y>0$), when the heating is stronger enough, the waves become southward-propagating again.

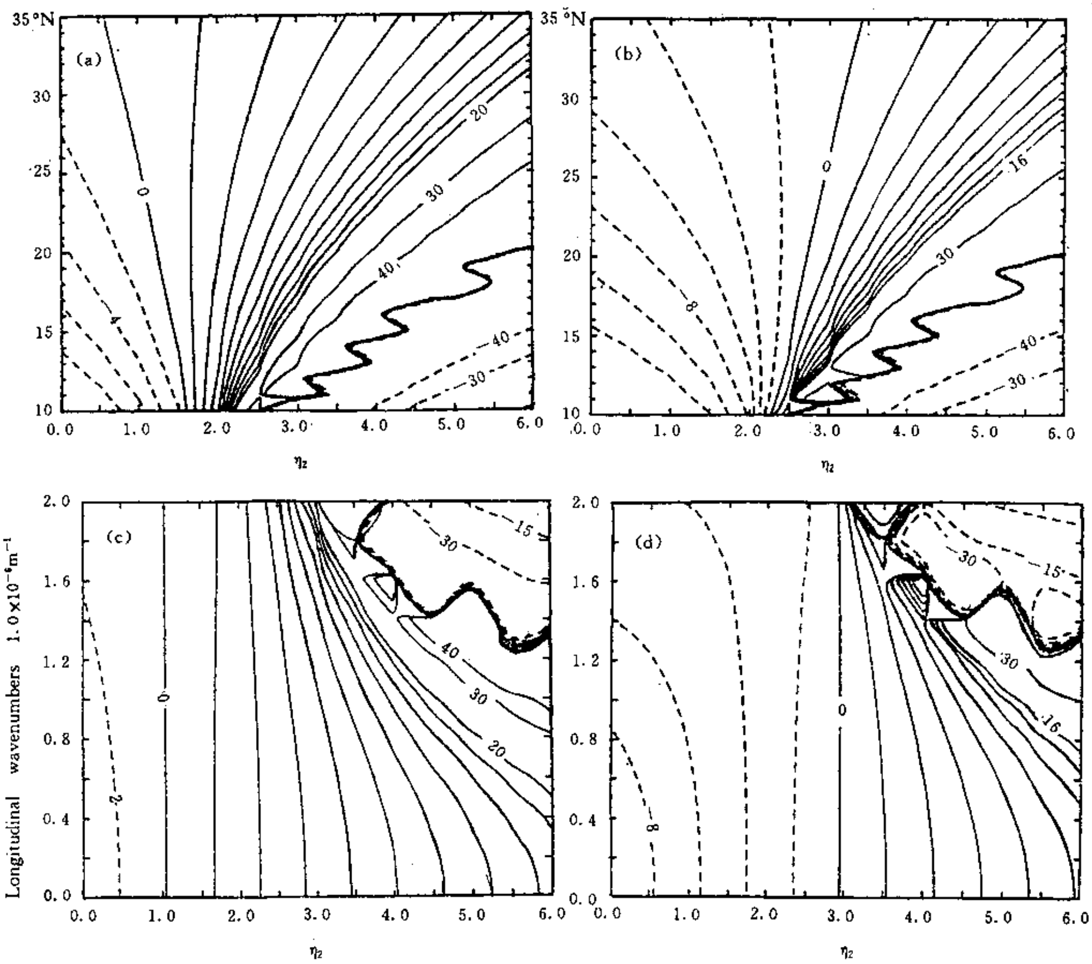

Fig. 2. Variation of c_x with η_2, latitudes and longitudinal wavenumbers, $\alpha<0$ for (a) and (c); $\alpha>0$ for (b) and (d). interval is 2 m s^{-1}.

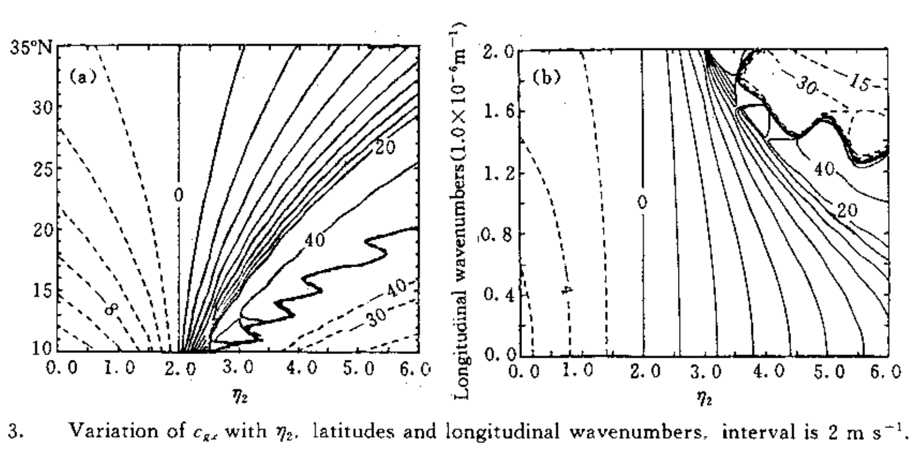

Fig. 3. Variation of c_{gx} with η_2, latitudes and longitudinal wavenumbers, interval is 2 m s^{-1}.

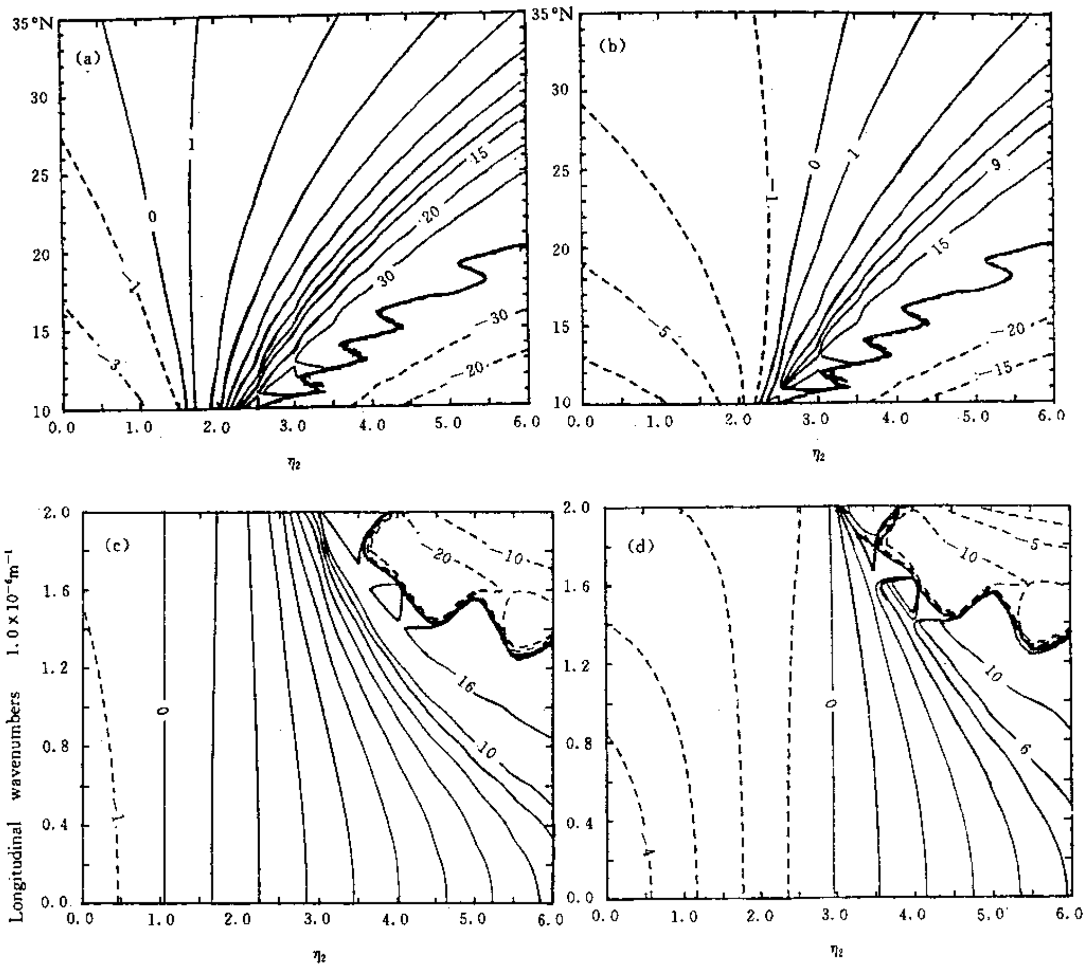

Fig. 4. Variation of c_y with η_2, latitudes and longitudinal wavenumbers. $\alpha<0$ for (a) and (c); $\alpha>0$ for (b) and (d), intervals are 2 m s^{-1} and 1 m s^{-1}.

The EWFM-CISK-Rossby waves described in this paper not only propagate eastward or northward but also could propagate westward or southward. And within the range of heating parameters in the real atmosphere, they propagate eastward at the speed of about 10 m s^{-1}, propagate northward at the speed of 1—3 m s^{-1}. These results are consistent with observational study of the 30—60 day oscillations . Observational data analyses have shown that the amplitude of 30-60 day oscillations of the tropical atmosphere do not decay obviously in the process of propagation, i. e. the existence of one kind of mechanism which counters to the energy dissipation and maintains disturbances. The EWFM-CISK-Rossby waves are unstably developing and not be dissipated during the propagation. From Eq. (10) it can be seen that wave growth rate is related to the mean surface flow, latitude, the latent heating and longitudinal wavenumbers (figures omitted).

The above analyses have shown that the waves become weakly dispersive in the zonal

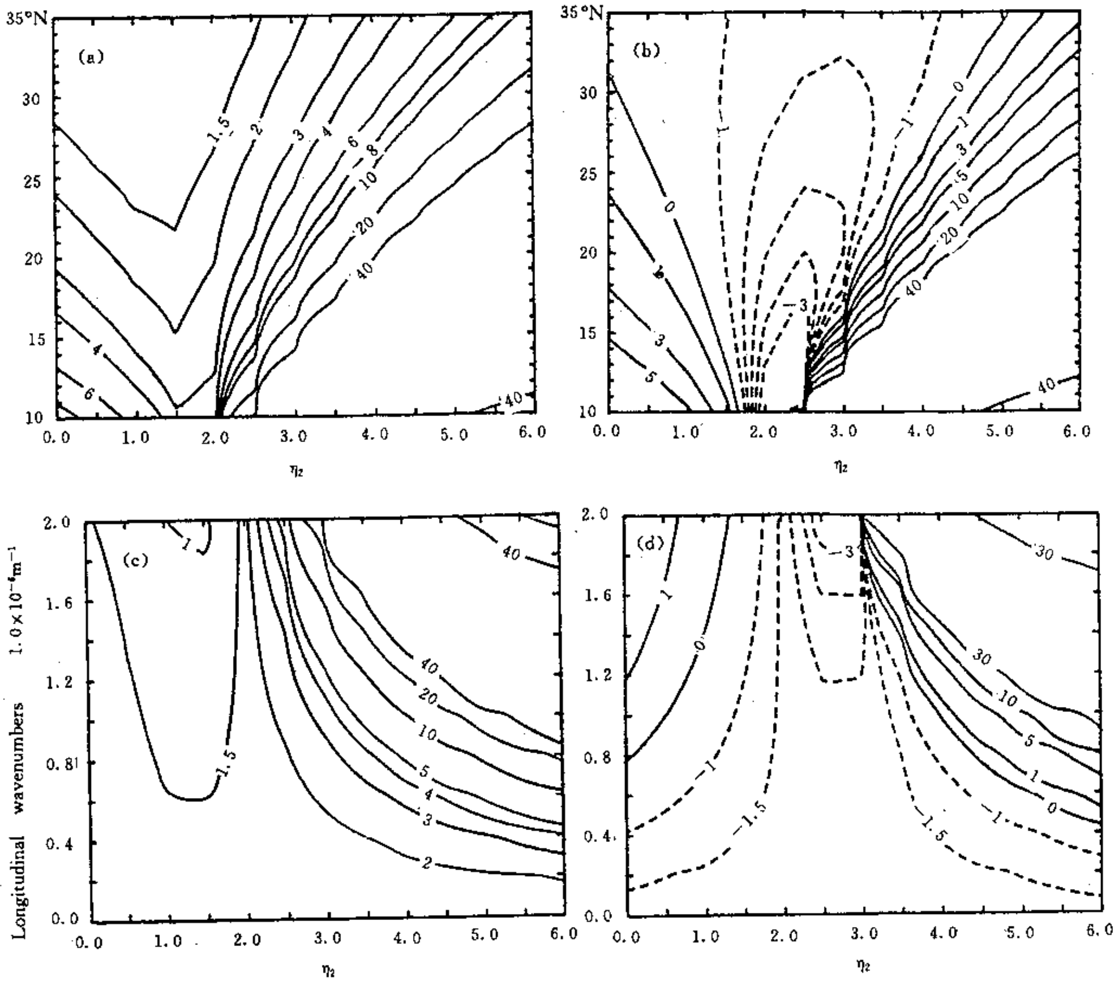

Fig. 5. Variation of c_{gy} with η_2, latitudes and longitudinal wavenumbers. $\alpha<0$ for (a) and (c); $\alpha>0$ for (b) and (d), interval is 0.5 m s^{-1}.

direction under the effect of EWFM. Figures 5a and 5b show c_{gy} as a function of the heating and latitudes at fixed wavelength ($L_y=6000$ km); Fig. 5c and 5d show c_{gy} as a function of the heating and wavenumbers at fixed latitude (25°N). A comparison between c_{gy} in Fig. 5 and c_y in Fig. 4 shows that they are quite different not only in numerical values but also in propagating orientations. this phenomenon demonstrates that the waves have strong dispersion in the meridional direction. And previous studies have shown that the 30—60 day oscillations of the tropical atmosphere have the characteristics of the two-dimensional Rossby wave trains. i. e. energy dispersion. Therefore, the EWFM-CISK-Rossby waves described in this paper are dispersive. From another point of view, these results further confirm that EWFM and CISK play an important role in triggering and driving the 30—60 day oscillations in the off-equatorial tropical atmosphere.

IV. LFO IN THE EQUATORIAL ATMOSPHERE

The foregoing analyses are those problems concerning the dynamical mechanism of LFO in the off-equatorial tropical atmosphere. If we study the problem of the LFO in the equatorial region, then the equatorial β-plane approximation may be taken into account, i.e. Coriolis parameter in Eqs. (1), (3) and (5) can be assumed to be $f=\beta y$, and the motion remains semigeostrophic. With these approximations, high frequency inertia-gravity waves, mixed Rossby-gravity waves as well as short Rossby waves are filtered out, and the analysis of moist equatorial Kelvin and long Rossby waves is greatly facilitated.

Firstly, we discuss the diabatic equatorial Rossby waves under the coactions of EWFM and CISK (the equatorial EWFM-CISK-Rossby waves, for short). In this case, $f=\beta y$, applying the normal mode method, we assume that Eq. (5) has the following wavelike solution

$$\hat{v} = V(y)e^{i(kx-\omega t)}, \tag{15}$$

and the boundary condition

$$\hat{v}|_{y\to\infty} = 0. \tag{16}$$

Substituting (15) into Eq. (5) and boundary condition (16) we obtain its eigenvalues

$$-L_0^2\left[\frac{\beta k}{\omega} - \frac{\lambda\alpha\beta i}{2\omega(1-b\eta_2)}\right] = 2m+1, \qquad (m=0,1,2\cdots), \tag{17}$$

corresponding eigenfunctions are

$$V(y) = B_m e^{-\left[\frac{1}{2L_0^2}-\frac{\lambda\alpha\beta}{4i\omega(1-b\eta_2)}\right]y^2} H_m(y/L_0), \tag{18}$$

where B_m is an arbitrary constant, $H_m=(y/L_0)$ is the mth order Hermite polynomial, and

$$\frac{1}{L_0^4} = \frac{\beta^2}{c_1^2(1-b\eta_2)} - \frac{\lambda^2\alpha^2\beta^2}{4\omega^2(1-b\eta_2)^2}. \tag{19}$$

Since $V(y)$ is limited by the boundary condition, from (18) we can get

$$\mathrm{Re}\left[\frac{\lambda\alpha\beta}{4i\omega(1-b\eta_2)} - \frac{1}{2L_0^2}\right] < 0. \tag{20}$$

Utilizing (17), then (20) can be rewritten as

$$\mathrm{Re}\left\{\frac{1}{\omega}\left[-\frac{(m+1)\lambda\alpha}{1-b\eta_2}i + k\right]\right\} < 0. \tag{21}$$

Re in (20) and (21) denotes the real parts of [ ] and { }, respectively. (20) or (21) is the main constraint which must be met in seeking for ω. Eliminating L_0 from (17) and (19), we obtain ω equation

$$\omega^2 = \frac{c_1^2}{(2m+1)^2}\left[\frac{m(m+1)1}{1-b\eta_2}\lambda^2\alpha^2 + k^2(1-b\eta_2) - ik\lambda\alpha\right]. \tag{22}$$

To obtain the solutions to the frequency equation (22), the constraint of Eq. (20) or (21) must be taken into account. In order to get the solutions to Eq. (22) under constraint (21), we set $\omega=\omega_r+i\omega_i$, qualitative analyses of ω_r and ω_i can get some important properties of the equatorial EWFM-CISK-Rossby waves. Substituting $\omega=\omega_r+i\omega_i$ into (21), we obtain

$$-\frac{\lambda\alpha(m+1)}{1-b\eta_2}\omega_i + k\omega_r < 0. \tag{23}$$

Multiplying (23) by $2\omega_r^2$, then (23) can be simplified to

$$\omega_r\left\{-\frac{\lambda\alpha(m+1)}{1-b\eta_2}\mathrm{Im}(\omega^2)+k[|\omega|^2+\mathrm{Re}(\omega^2)]\right\}<0, \tag{24}$$

where Im and Re represent imaginary and real parts of ω^2 respectively, and using (22), then (24) can be reduced to

$$\omega_r\left[|\omega|^2+\frac{(m+1)^2\lambda^2\alpha^2}{1-b\eta_2}+k^2(1-b\eta_2)\right]<0. \tag{25}$$

It is easy to prove that the term [ ] in (25) and $(1-b\eta_2)$ have the same sign, so we have

$$\mathrm{sgn}(\omega_r)=-\,\mathrm{sgn}(1-b\eta_2). \tag{26}$$

On the other hand, multiplying (23) by $2\omega_i^2$ and using (22), then (23) is transformed to

$$\omega_i\frac{\lambda\alpha(m+1)}{1-b\eta_2}\left[1-\frac{\dfrac{m(m+1)\lambda^2\alpha^2}{1-b\eta_2}+\dfrac{mk^2(1-b\eta_2)}{m+1}}{|\omega|^2}\right]>0. \tag{27}$$

It is easy to prove that the term [ ] in (27) is always positive, so we have

$$\mathrm{sgn}(\omega_i)=\mathrm{sgn}(\alpha)\cdot\mathrm{sgn}(1-b\eta_2). \tag{28}$$

Equations (26) and (28) include the important properties of the equatorial EWFM-CISK-Rossby waves: under the condition $b\eta_2<1$, if the mean zonal flow is westerlies ($\alpha<0$), then the equatorial EWFM-CISK-Rossby waves are westward-propagating ($\omega_r<0$) and decaying ($\omega_i<0$); if the mean zonal flow is easterlies ($\alpha>0$), then the equatorial EWFM-CISK-Rossby waves are westward-propagating ($\omega_r<0$) and developing ($\omega_i>0$). Under the condition $b\eta_2>1$, if the mean zonal flow is westerlies ($\alpha<0$) then the equatorial EWFM-CISK-Rossby waves are eastward-propagating ($\omega_r>0$) and developing ($\omega_i>0$); if the mean zonal flow is easterlies ($\alpha>0$), then the equatorial EWFM-CISK-Rossby waves are eastward-propagating ($\omega_r>0$) and decaying ($\omega_i<0$). It can be seen clearly that EWFM and CISK have changed the properties of the equatorial Rossby waves.

Secondly, we study the diabatic Kelvin waves under the effects of EWFM and CISK (the EWFM-CISK-Kelvin waves, for short). Similar to the previous procedures, we obtain the EWFM-CISK-Kelvin waves' frequency equation as follows

$$\omega^2=k^2c_1^2(1-b\eta_2)-ik\lambda\alpha c_1^2, \tag{29}$$

and

$$\begin{cases}\omega_r>0,\\ \mathrm{sgn}(\omega_i)=-\,\mathrm{sgn}(\alpha).\end{cases} \tag{30}$$

It is clear that the EWFM-CISK-Kelvin waves are eastward-propagating, unstable and dispersive. When the mean zonal flow is easterlies ($\alpha>0$) the waves are decaying ($\omega_i<0$); when the mean zonal flow is westerlies ($\alpha<0$), the waves are developing ($\omega_i>0$).

In equatorial atmosphere, the diabatic Kelvin and Rossby waves are eastward-propagating and westward-propagating, respectively. Both are stable. It is clear that they are not the triggering mechanism of the LFO. As for the CISK-Kelvin waves without EWFM, if the heating is weak, e.g. $\eta_2=1.6-1.8$, then $c_x=15-10$ m s^{-1}. The waves slowly propagate eastward and are close to the speed of the observed eastward-propagating 30-60 day oscillations, but the waves are stable; if the heating is strong, e.g. $\eta_2>2.0$, then $c_x=0$, $\omega_i>0$, the waves are stationary but unstable (developing). Therefore although we use a simple 2-layer model atmosphere, the CISK-Kelvin waves obtained in this paper have slowly eastward-propagating characteristics, and the results are similar to that of multi-layer model (Takahashi 1987). Analyses of Takahashi's 3-layer model have shown that, within a wide range of the heating parameter, the disturbances are stable and those unstable disturbances are stationary, only within a very narrow range of the heating parameter can those disturbances not only propagate eastward but also be unstable. Utilization of those slowly eastward-propagating CISK-Kelvin waves, we may explain the slowly eastward moving processes of the 30—60 day oscillations in the equatorial region, but the waves are non-dispersive and the situations of the two-dimensional Rossby wave trains can not be formed. On the other hand, the eastward-propagating waves are in general stable and may decay during the propagation, these are inconsistent with the fact that the amplitude of 30—60 day oscillations does not decay during eastward movement. Therefore, it is still imperfect that the CISK-Kelvin waves are regarded as the dynamic mechanism of 30—60 day oscillations in the tropical atmosphere. As for the equatorial CISK-Rossby waves without EWFM, if the heating is weak, the waves propagate westward at the reduced phase speed and stabe; if the heating is strong, the waves are stationary but unstable (decaying), and the equatorial CISK-Rossby waves are also non-dispersive. It is clear that the equatorial CISK-Rossby waves in the 2-layer model can not account for the slowly eastward-propagating 30—60 day oscillations of the equatorial region.

Qualitative analyses have pointed out that the equatorial EWFM-CISK-Rossby waves are unstable dispersive waves whose propagating orientations depend on the latent heating; the EWFM-CISK-Kelvin waves are eastward-propagating, unstable, dispersive waves. By calculating latent heating from (29), then $c_x=\omega_r/k$, $|\omega_i|$ of the EWFM-CISK-Kelvin waves are as the functions of wavelengths (see Fig. 6). It can be seen that c_x increases with the wavelength and decreases with the heating strengthening. For different wavelengths, if the heating strength is proper, all waves can get the phase speed of $c_x=11$ m s^{-1} or so, this is close to the observed speed of slowly eastward-propagating 30—60 day oscillations in the tropical atmosphere. $|\omega_i|$ decreases with the increase of the wavelength, and increases with the heating strengthening. Therefore, the phase speed and the developing (decaying) rate of the EWFM-CISK-Kelvin waves may vary dramatically with variations of heating and wavelengths. With the heating becoming strong, the phase speed decreases greatly, the developing (decaying) rate increases. As for short waves, their phase speeds are small, and their developing (decaying) rates are large, so they can not propagate over a long distance. Only those ultralong waves have smaller developing (decaying) rates and large phase speeds, so they can propagate over longer distance. Similarly, from (22) we can calculate $|c_x|=|\omega_r|/k$, then $|\omega_i|$ $(m=0,1,2,\cdots)$ of the equatorial EWFM-CISK-Rossby waves will be the functions of wavelengths and the heating (figures omitted). Same analyses can be made, it is noted that, when $\eta_2>2.0$, the phase speed of the eastward-propagating equatorial EWFM-CISK-Rossby waves decreases with the increase of m, thus, even very low frequency waves appear.

In conclusion, the 30-60 day oscillations in the equatorial region are the low-frequency response to the coactions of EWFM and CISK by the Kelvin and equatorial Rossby waves.

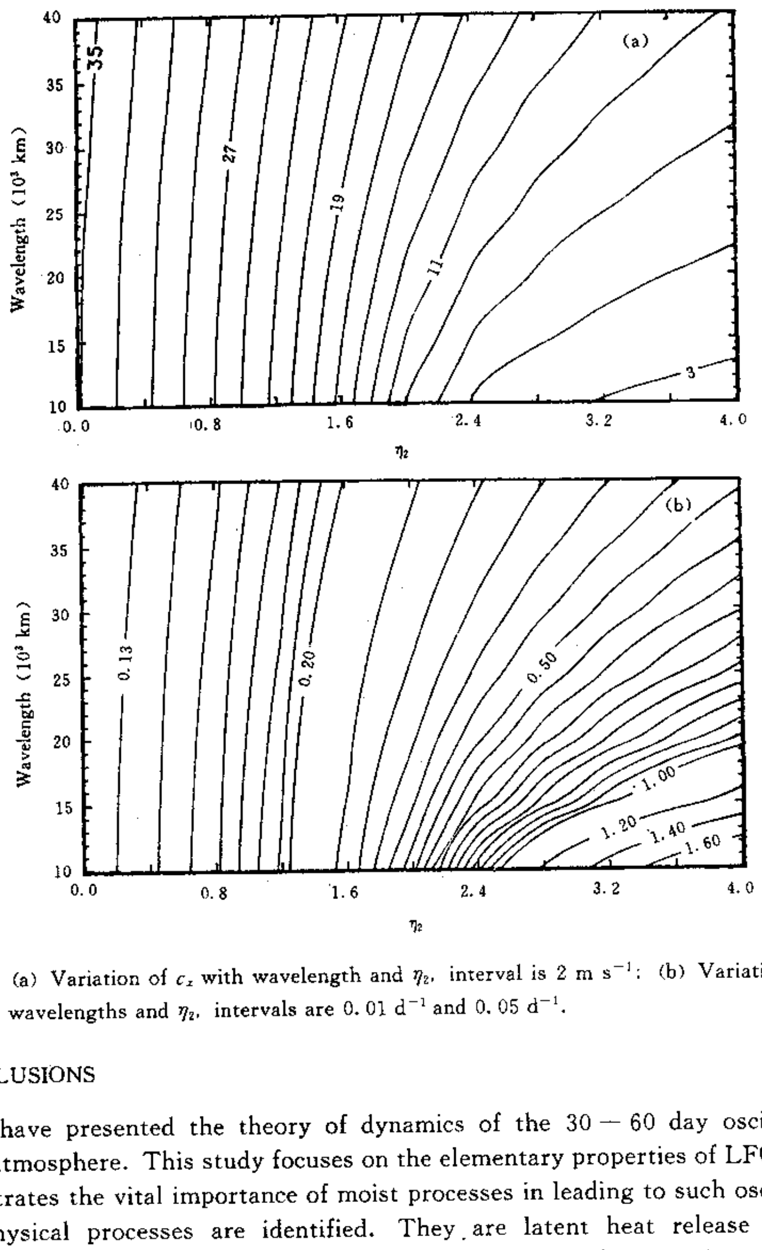

Fig. 6. (a) Variation of c_x with wavelength and η_2, interval is 2 m s^{-1}; (b) Variation of $|\omega_i|$ with wavelengths and η_2, intervals are 0.01 d^{-1} and 0.05 d^{-1}.

V. CONCLUSIONS

We have presented the theory of dynamics of the 30 — 60 day oscillations in the tropical atmosphere. This study focuses on the elementary properties of LFO in the tropics and illustrates the vital importance of moist processes in leading to such oscillations. Two major physical processes are identified. They are latent heat release through CISK mechanism and EWFM in the atmosphere. The presence of interactive moisture (CISK mechanism) in the tropical atmosphere causes atmospheric motions to slow down through a reduction of the effective moist static stability of the lower troposphere. The presence of EWFM tends to cause atmospheric waves to move eastward (westward) in the presence of mean surface easterlies (westerlies), it also reinforces the CISK mechanism. Adiabatic Kelvin and Rossby waves are quite different from the characteristics of 30 — 60 day oscillations, on the other hand, the so-called EWFM-CISK-Kelvin waves and EWFM-CISK-Rossby waves obtained in this paper both underline the importance of diabatic moist processes in giving rise to the LFO. Therefore, we may believe that EWFM and CISK mechanisms are very important physical processes in triggering and driving the 30—60 day oscillations of the tropical atmosphere. The mechanisms suggested by the present study are easy to understand so that more sophisticated models can be built on. It is likely that dissipation and nonlinear effects will further modify the results described in this paper. These details need to worked out in further studies.

REFERENCES

Chen Longxun et al. (1988). Westward propagation low-frequency oscillation and its teleconnections in the Eastern Hemisphere. *Acta Meteor. Sinica*, **2**: 300—312.

Emanuel, K. A. (1987). An air-sea interaction model of intra-seasonal oscillation in the tropics. *J. Atmos. Sci.*, **44**: 2224—2240.

Hayashi, Y. (1970). A theory of large-scale equatorial waves generated by condensation heat and accelerating the zonal wind. *J. Meteor. Soc. Japan*, **48**: 140—160.

Knutson, T. R. and Weickmann, K. M. (1987). The 30—60 day atmospheric oscillations: composite life cycles of convection and circulation anomalies. *Mon. Wea. Rev.*, **115**: 1407—1436.

Lau, K. M. and Chan, P. H. (1985). Aspects of the 40—50 day oscillation during the Northern Winter as inferred from outgoing longwave radiation. *Mon. Wea. Rev.*, **113**: 1889—1909.

Lau, N. C. and Lau, K. M. (1986). The structure and propagation of oscillations appearing in a GFDL general circulation model. *J. Atmos. Sci.*, **43**: 2023—2047.

Lau, K. M. and Peng, L. (1987). Origin of low-frequency (intraseasonal) oscillations in the tropical atmosphere. Part I: Basic theory. *J. Atmos. Sci.*, **44**: 950—972.

Li Chongyin (1990). A study of dynamics of 30 — 50 day oscillations in the off-equatorial tropical atmosphere. *Sci. Atmos. Sinica*, **14**: 83—92 (in Chinese).

Lindzen, R. S. (1974). Wave-CISK in the tropics. *J. Atmos. Sci.*, **31**: 156—179.

Liu Shikuo and Wang Jiyong (1992). A baroclinic semi-geostrophic model using the wave-CISK theory and low-frequency oscillation. *Acta Meteor. Sinica*, **50**: 393—402 (in Chinese).

Madden, R. A. and Julian, P. R. (1971). Detection of a 40—50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**: 702—708.

Madden, R. A. and Julian, P. R. (1972). Description of a global scale circulation cells in the tropics with 40—50 day period. *J. Atoms. Sci.*, **29**: 1109—1123.

Miyahara, S. (1987). A simple model of the tropical intraseasonal oscillation. *J. Meteor. Soc. Japan*, **65**: 340—351.

Murakami, T. and Nakazawa, T. (1985). Tropical 45 day oscillations during the 1979 Northern Hemisphere summer. *J. Atmos. Sci.* **42**: 1107—1122.

Nakazawa, T. (1986). Mean features of 30—60 day variations as inferred from 8-year OLR. *J. Meteor. Soc. Japan*, **65**: 43—49.

Neelin, J. D. et al. (1987). Evaporation-wind feedback and low-frequency variability in the tropical atmosphere. *J. Atmos. Sci.*, **44**: 2341—2348.

Takahashi, M. (1987). A theory of the slow phase speed of the intraseasonal oscillation using the wave-CISK. *J. Meteor. Soc. Japan*, **65**: 42—49.

Yasunari, T. (1979). Cloudiness fluctuations associated with the Northern Hemisphere summer monsoon. *J. Meteor. Soc. Japan*, **57**: 227—242.