FURTHER STUDIES ON EVAPORATION-WIND FEEDBACK

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Received 16 February 1995, accepted 29 May 1995

ABSTRACT

The results from simple dynamic studies on the evaporation-wind feedback show that the effect cannot change the nature of tropical atmospheric waves (by retarding the speed), so that the evaporation-wind feedback alone cannot be an exciting mechanism of intraseasonal oscillation in the tropical atmosphere. This is different from that of the wave-CISK mechanism. With combined effect of the cumulus convection heating and evaporation-wind feedback, the CISK-Kelvin waves and CISK-Rossby waves will develop unstably, explaining the dynamic mechanism of tropical intraseasonal oscillation in a more complete and reasonable way than the convection heating alone. Therefore, the evaporation-wind feedback is also important to the intraseasonal oscillation in the tropical atmosphere.

Key words: evaporation-wind feedback, CISK mechanism, intraseasonal oscillation in the tropical atmosphere

I. INTRODUCTION

The evaporation-wind feedback was advanced to account the dynamic mechanism of intraseasonal oscillation in the tropical atmosphere by Emanuel and Neelin et al., in 1987. According to their theory, the responsive fields for the easterly and westerly will be forced respectively at the east side and west side of the convection region in the lower troposphere by the cumulus convection activities. If these perturbation (response) winds are superposed on mean easterlies, as in the tropics, the strength of the surface zonal wind will increase to the east of the convection and decrease to the west. Thus the evaporation will also increase to the east and decrease to the west; the convection at east side will be also stronger than that at west side. These processes form a feedback and resulting feedback can favour or create eastward-propagation modes. Therefore, the evaporation-wind feedback was regarded as a dynamic mechanism to excite tropical intraseasonal oscillation, especially to explain the eastward propagation of tropical intraseasonal oscillation.

The evaporation-wind feedback was still introduced into the wave-CISK mechanism for tropical intraseasonal oscillation (Lau and Shen, 1988; Li and Liu 1993). But the exact effect of the evaporation-wind feedback, especially its limitation, is not understood very well. In this paper, the feature of evaporation-wind feedback will be discussed in dynamics and its effect on tropical intraseasonal oscillation will be understood completely.

II. EVAPORATION-WIND FEEDBACK ALONE

In order to understand the feature of evaporation-wind feedback mechanism, at first we discuss the case with evaporation-wind feedback alone. As the study in Hayashi (1970), on an equatorial beta plane, the governing equations can be written as follows.

$$\frac{\partial u}{\partial t} - \beta y v + \frac{\partial \phi}{\partial x} = 0 \tag{1}$$

$$\beta y u + \frac{\partial \phi}{\partial y} = 0 \tag{2}$$

$$\frac{\partial \phi}{\partial t} + C_0^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = - D_0 u \tag{3}$$

where D_0 is the evaporation-wind feedback parameter, $D_0 > 0$ in easterly region and $D_0 < 0$ in westerly region; C_0 is phase speed of the atmospheric gravity wave.

Taking time scale $T_0 = \sqrt{1/2\beta C_0}$, horizontal space scale $L_0 = \sqrt{C_0/2\beta}$, the nondimensional equations for Eqs. (1) ~ (3) will be the same to them in the formality. Assuming $\alpha_0 = D_0/C_0\sqrt{2C_0\beta}$, the equations can become

$$\frac{\partial u}{\partial t} - \frac{1}{2} y v + \frac{\partial \phi}{\partial x} = 0 \tag{4}$$

$$\frac{1}{2} y u + \frac{\partial \phi}{\partial y} = 0 \tag{5}$$

$$\frac{\partial \phi}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = - \alpha_0 u. \tag{6}$$

Asssuming the solutions are as the following form

$$(u, v, \phi) = (U, V, \Phi) e^{i(kx - \sigma t)}$$

from Eqs. (4) ~ (6), we have

$$- i\sigma U - \frac{1}{2} y V + ik\Phi = 0 \tag{7}$$

$$\frac{1}{2} y U + \frac{\mathrm{d}\Phi}{\mathrm{d}y} = 0 \tag{8}$$

$$- i\sigma\Phi + ikU + \frac{\mathrm{d}V}{\mathrm{d}y} = - \alpha_0 U. \tag{9}$$

Eliminating Φ from (7) and (8), we obtain

$$- i\sigma \frac{\mathrm{d}U}{\mathrm{d}y} - \frac{1}{2} V - \frac{1}{2} y \frac{\mathrm{d}V}{\mathrm{d}y} - i\frac{k}{2} y U = 0 \tag{10}$$

and

$$U = \frac{\left(\frac{1}{2}\sigma y V - k\frac{\mathrm{d}V}{\mathrm{d}y}\right)}{[\alpha_0 k + i(k^2 - \sigma^2)]} \tag{11}$$

from (7) and (9). Finally, the equation in relation to the variable V alone can be written as follows:

$$\frac{\mathrm{d}^2 V}{\mathrm{d}y^2} + \frac{i\alpha_0}{2\sigma} y \frac{\mathrm{d}V}{\mathrm{d}y} - \left(\frac{V - i\alpha_0}{2\sigma} + \frac{1}{4} y^2\right) V = 0 \tag{12}$$

Taking

$$V = B e^{\frac{-i\alpha_0 y^2}{8\sigma}} \tag{13}$$

and

$$y = \left(1 - \frac{\alpha_0^2}{4\sigma^2}\right)^{-\frac{1}{4}} Y \tag{14}$$

the equation (12) can be written as

$$\frac{d^2 B}{dY^2}+\left[\left(1-\frac{\alpha_0^2}{4\sigma^2}\right)^{-\frac{1}{2}}\left(-\frac{2k-i\alpha_0}{4\sigma}\right)-\frac{Y^2}{4}\right]B=0. \tag{15}$$

In order to satisfy the boundary condition: the B value is finite at $Y(y)\to\pm\infty$, according to the fundamentals of differential equations, there should be a relation as follows:

$$2\left(1-\frac{\alpha_0^2}{4\sigma^2}\right)^{-\frac{1}{2}}\left(-\frac{2k-i\alpha_0}{4\sigma}\right)=(2m+1)$$

or it can be written as

$$(2k-i\alpha_0)^2=(2m+1)^2(4\sigma^2-\alpha_0^2) \tag{16}$$

and the solution of Eq. (15) is

$$B(\zeta)=Ae^{-\frac{1}{2}\zeta^2}H_m(\zeta) \tag{17}$$

where H_m is Hermite polynomial, m is parameter in relation to the wavenumber in y-direction; A can be regarded as the amplitude, and $\zeta=\frac{1}{2}Y$. In this paper, we just focus to discuss the frequency and leave the exact expression of solution out of consideration.

Since $\sigma=\sigma_r+i\sigma_i$, σ_r and σ_i is respectively the growth rate and frequency of the atmospheric perturbation, from (16) we can obtain

$$\sigma_i=-\frac{\alpha_0 k}{2(2m+1)^2\sigma_r} \tag{18}$$

$$\sigma_r=-\frac{1}{2(2m+1)}\sqrt{\frac{4k^2+G_0^2\pm\sqrt{(4k^2+G_0^2)^2+16\alpha_0^2k^2}}{2}} \tag{19}$$

where $G_0^2=\alpha_0^2[(2m+1)^2-1]$.

In Eq. (19), the negative root of evolution is selected because the Kelvin waves ($m=-1$) should propagate eastwards ($\sigma_r>0$) and the Rossby waves ($m=1,2,\ldots$) should propagate westwards in the tropical atmosphere without evaporation-wind feedback ($\alpha_0=G_0=0$).

As we know, if there are not the evaporation-wind feedback and cumulus heating feedback, the Kelvin waves in the tropical atmosphere will propagate eastwards very fast and the speed is $C_x\approx 50$ m/s in general. When there is cumulus convection heating in the tropical atmosphere, the feature of faster Kelvin waves is modified, so that they become CISK-Kelvin waves which propagate eastwards ($C_x\approx 10$ m/s). Therefore, the CISK-Kelvin wave theory can be regarded as a dynamic mechanism of intraseasonal oscillation in the tropical atmosphere. But when there is evaporation-wind feedback alone (without cumulus heating , as shown in (19), the evaporation-wind feedback will not affect the propagation of Kelvin waves, so that the Kelvin waves still propagate quickly eastwards in this case;the Rossby waves will propagate acceleratively westwards in this case. Obviously, it is difficult to account for the dynamic mechanism of tropical intraseasonal oscillation using these waves with evaporation-wind feedback alone. In other words, without the cumulus convection heating, evaporation-wind feedback alone cannot excite intraseasonal oscillation in the tropical atmosphere, and only the tropical waves propagating quickly can be excited.

But, we can see from (18) that the influence of evaporation-wind feedback on the instability of waves is obvious. In mean easterlies ($a_0 > 0$), the Kelvin waves ($\sigma_r > 0$) are unstable growth ($\sigma_i > 0$) and Rossby waves ($\sigma_r < 0$) are attenuation ($\sigma_i < 0$) as a result of evaporation-wind feedback; In mean westerlies ($a_i < 0$), the Kelvin waves are attenuation ($\sigma_i < 0$) and Rossby waves are unstable growth ($\sigma_i > 0$) as a result of evaporation-wind feedback. This obvious effect of the evaporation-wind feedback to the instability of atmospheric waves is very important in tropical atmospheric motion and the result is consistent with the action of tropical intraseasonal oscillation.

In order to understand the dynamic nature of evaporation-wind feedback, a schematic diagram is shown in Fig. 1. Where $\bar{u}$ is basic flow (easterly), the dotted lines represent atmospheric waves associated with convection. From time t_1 to time t_2, there is more strong convection on the east side of previous convection and the atmospheric waves propagate eastwards as a result of evaporation-wind feedback. It is clear that the tropical atmospheric waves are unstable and propagating due to the effect of evaporation-wind feedback, however, the propagation of waves is still fast and means that the evaporation-wind feedback cannot retard the atmospheric waves.

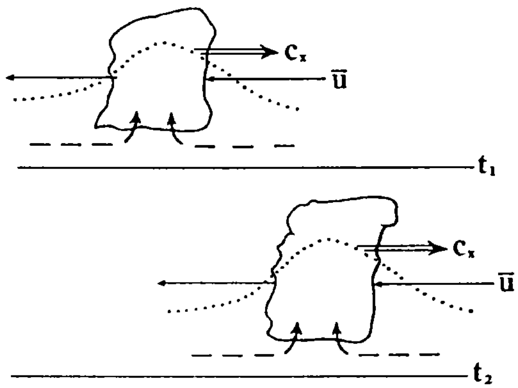

Fig. 1. Schematic diagram of tropical wave with the evaporation-wind feedback.

Ⅲ. COMBINED EFFECT OF CUMULUS HEATING AND EVAPORATION-WIND FEEDBACK

Some studies have indicated that the cumulus convection heating feedback (wave-CISK) is an important mechanism to excite intraseasonal oscillation in the tropical atmosphere (Li, 1985; Lau and Peng, 1987; Takahashi, 1987; Li, 1990; Liu and Wang, 1990), for which, the CISK-Kelvin wave and CISK-Rossby wave will be produced in the tropics. But it is difficult to find that the CISK-Kelvin wave is both eastward propagating and unstable, because in most parameter domain, the eastward propagating CISK-Kelvin wave is stable and the unstable CISK-Kelvin wave is stationary. This shows the deficiency of wave-CISK theory for intraseasonal oscillation in the tropical atmosphere. The important effect of the evaporation-wind feedback on instability of tropical atmospheric waves has been indicated in the secton above. In this section, we will discuss the feature of CISK modes in the case with both the cumulus heating and evaporation-wind feedback using simple dynamic model.

On the equatorial beta plane, the governing equations with the cumulus convection heating and evaporation-wind feedback for tropical intraseasonal oscillation can be written as follows:

$$\frac{\partial u}{\partial t} - \beta y v = - \frac{\partial \phi}{\partial x} \tag{20}$$

$$\beta y u = - \frac{\partial \phi}{\partial y} \tag{21}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{22}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial z}\right) + N^2 w = N^2 \eta w_B - \alpha_0 N^2 u \tag{23}$$

in which the first term of right hand side in Eq. (23) represents the convection heating which depends on the heating function η and vertical velocity at the top of boundary layer (w_B); the second term represents evaporation-wind feedback.

In the tropical atmosphere, the vertical velocity at the top of boundary layer can be simply represented by using vertical velocity in the free atmosphere, i. e. $w_B = bw$, where $b < 1$. Taking 2-level model shown in Fig. 2 and according to the vertical distribution of atmospheric velocity field, we can use the following approximation relations: $w_2 = w_1 - w_3, u_2 = u_1 - u_3 = 2\hat{u}$, $(\hat{u}, \hat{v}, \hat{\phi}) = \frac{1}{2}[(u_1 - u_3), (v_1 - v_3), (\phi_1 - \phi_3)]$

Thus, Eqs. (20) — (23) can be written as follows:

$$\frac{\partial \hat{u}}{\partial t} - \beta y \hat{v} = - \frac{\partial \hat{\phi}}{\partial x} \tag{24}$$

$$\beta y \hat{u} = - \frac{\partial \hat{\phi}}{\partial y} \tag{25}$$

$$\frac{\partial \hat{\phi}}{\partial t} + C_0(1 - b\eta_2)\left(\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y}\right) = - D_1 \hat{u} \tag{26}$$

where $C_0 = \frac{\sqrt{2}}{2} N\Delta$, Δ is vertical interval in the model, for the model atmosphere in present, $C_0 \approx 50$ m/s; D_1 represents evaporation-wind feedback parameter.

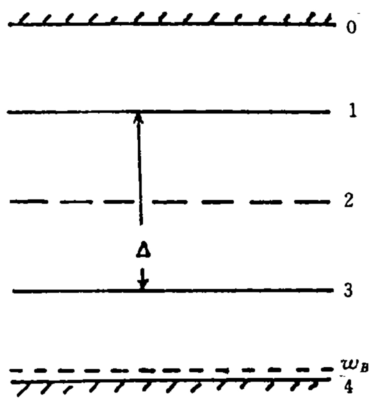

Fig. 2. Dividing layers of the model atmosphere.

According to previous study in relation to the tropical atmospheric thermodynamics (Hayashi, 1970), $\eta_2 \approx 1.8 \sim 2.4$ for general convection heating in the tropical atmosphere; and $b \approx 0.4 \sim 0.6$ in general. Thus, we can obtain phase speed of the wave $C_1 = C_0(1 - b\eta_2) \approx 10$ m/s in the case with the cumulus convection heating to tropical atmospheric wave.

We can see that the Eqs. (24) $\sim$ (26) are the same in form as the Eqs. (1) $\sim$ (3). Therefore, following the treatment used in the section above, but taking time scale $T_1 = \sqrt{\frac{1}{2\beta C_1}}$, horizontal space scale $L_1 = \sqrt{\frac{C_1}{2\beta}}$, we can also obtain the nondimensional equations for Eqs. (24) $\sim$ (26). Finally, we can obtain the growth rate σ_i and frequency σ_r of tropical atmospheric waves in the case with combined effect of the cumulus heating and evaporation-wind feedback as follows:

$$\sigma_i = \frac{\alpha_1 k}{2(2m+1)^2 \sigma_r} \tag{27}$$

$$\sigma_r = -\frac{1}{2(2m+1)}\sqrt{\frac{4k^2 + G_1^2 + \sqrt{(4k^2 + G_1^2)^2 + 16a_1^2k^2}}{2}} \qquad (28)$$

where $a_1 = \dfrac{D_1}{C_1\sqrt{2C_1\beta}}$; $G_1^2 = a_1^2[(2m+1)^2 - 1]$; k and m is the wavenumber in x-and y-direction, respectively.

If there is not the evaporation-wind feedback in (27) and (28), $a_1 = 0, G_1 = 0$, we can obtain the CISK-Kelvin wave and CISK-Rossby wave in the tropical atmosphere as discussed in previous studies. For the present model, these waves are stable ($\sigma_i = 0$) but their speed is about 10 m/s which approaches to one of the observed intraseasonal oscillation in the tropical atmosphere.

If there are both the evaporation-wind feedback and convection heating in (27) and (28), $a_1 \neq 0, G_1 \neq 0$, the evaporation-wind feedback is unable to change the speed of eastward CISK-Kelvin waves but can accelerate the speed of westward CISK-Rossby waves. Because the CISK-Kelvin waves and CISK-Rossby waves have been slower propagating waves, so that these waves can still be regarded as dynamic mechanism to drive intraseasonal oscillation in the tropical atmosphere. Simultaneously, the CISK-Kelvin waves and CISK-Kelvin waves will be unstable since the existence of evaporation-wind feedback, for example, the CISK-Kelvin waves will develop unstably in the easterlies ($a_0 > 0$).

Therefore in the case with the combined effect of the cumulus heating and evaporation-wind feedback, the CISK-Kelvin waves and CISK-Rossby waves in the tropical atmosphere are not only slow propagation with the speed approaching to the observed intraseasonal oscillation, but also unstable. These kinds of CISK-Kelvin waves and CISK-Rossby waves can be used to explain the important feature of the observed intraseasonal oscillation which is not reduced as propagation.

The schematic diagram in the case with combined effect of the cumulus heating and evaporation-wind feedback is shown in Fig. 3. The consistence represented in Fig. 3 and Fig. 1 is that the waves (of low frequency) are both propagational and unstable; but the difference is that the speed of waves is reduced by the effect of cumulus heating feedback. In other words, tropical atmospheric low-frequency waves are slow propagation and unstable in the case with the cumulus heating and evaporation-wind feedback, these features are consistent with the observed intraseasonal oscillation.

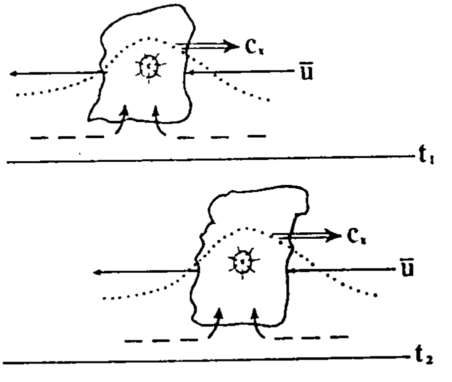

Fig. 3. Schematic diagram of tropical wave with the cumulus convection heating and evaporation-wind feedback.

IV. CONCLUSIONS

A lot of studies have indicated that the cumulus convection heating is important mechanism to excite intraseasonal oscillation in the tropical atmosphere. It is still not clear how the evaporation-wind feedback acts in exciting tropical intraseasonal oscillation, even though it was also regarded as a mechanism. Some dynamic analyses in relation to the evaporation-wind feedback in this paper have obtained interesting results.

Different from the wave-CISK mechanism, the evaporaton-wind feedback is unable to change the nature of tropical atmospheric wave (retardation), so that it cannot excite tropical waves, like the intraseasonal oscillations in the tropical atmosphere. Therefore, evaporation-wind feedback alone cannot be dynamic mechanism of intraseasonal oscillation in the tropical atmosphere.

The evaporation-wind feedback will lead to unstable development of tropical atmospheric waves, the Kelvin waves will be unstable in the easterlies and the Rossby waves will be unstable in the westerlies. Therefore, the CISK-Kelvin waves and CISK-Rossby waves can be unstable as slow propagation, which approach the speed of the observed intraseasonal oscillation in the tropical atmosphere, in the case with combined effect of the cumulus convection heating and evaporation-wind feedback. Thus, more completely, it should be suggested that the combined effect of the cumulus convection heating and evaporation-wind feedback is dynamic mechanism of intraseasonal oscillation in the tropical atmosphere.

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