CISK Kelvin Wave with Evaporation–Wind Feedback and Air–Sea Interaction—A Further Study of Tropical Intraseasonal Oscillation Mechanism

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(Received May 18, 2001; revised October 22, 2001)

ABSTRACT

The wave–CISK (cumulus convection heating feedback), the air–sea interaction and the evaporation–wind feedback are together introduced into a simple theoretical model, in order to understand their effect on driving tropical atmospheric intraseasonal oscillation (ISO). The results showed that among the introduced dynamical processes the wave–CISK plays a major role in reducing phase speed of the wave to be closer to the observed tropical ISO. While the evaporation–wind feedback plays a major role in unstabilizing the wave. The air–sea interaction has certain effect on slowing down the phase speed of the wave. Therefore, the wave–CISK and evaporation–wind feedback can be regarded as fundamental dynamical mechanism of the tropical ISO. This study also shows that since the effects of the evaporation–wind feedback and the air–sea interaction were introduced, the excited wave is zonally dispersive, which can dynamically explain the activity feature of the observed ISO in the tropical atmosphere very well.

Key words: Intraseasonal oscillation, CISK Kelvin wave, Evaporation–wind feedback, Air–sea interaction

1. Introduction

Since the intraseasonal (30–60 day) oscillation was identified in the early of 1970s (Madden and Julian 1971; 1972), its general characteristics and activity regulations have been investigated in series studies (Krishnamurti and Subrahmanyam 1982; Murakami 1984; Lau and Lau 1986; Knuston and Weickmann 1987; Li 1991; Madden and Julian 1994). So therefore the existence and activity of tropical ISO as an atmospheric system in the tropics have not been suspected wholly.

The cumulus convection heating feedback (wave–CISK) was introduced first in 1985 as the dynamical mechanism of the ISO in the tropical atmosphere (Li 1985). The theoretical analysis showed that the moving CISK mode due to the cumulus convection heating can cause the ISO in Asian monsoon region since the convection heating feedback will reduce the phase speed of the excited wave to be closer to the propagation speed of the observed ISO in tropical atmosphere through changing atmospheric stratification. The convection heating feedback as an important mechanism of tropical ISO was also discussed by Lau and Peng

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(1987) in the study of the origin of low–frequency (intraseasonal) oscillation in the tropical atmosphere. In the meantime, the influence of convection heating profile on phase speed of the excited tropical wave was studied and it was shown that the stronger heating in the middle–lower troposphere will lead phase speed of the excited wave to be closer to that of the observed ISO (Takahashi 1987). The further studies showed that the excited wave will become unstable under the effects of the vertical modes interaction (Chang and Lim 1988) and the moist atmospheric boundary layer (Wang 1988), which can be more advantageous to explain the activities of tropical ISO. In early 1990s, the theoretical studies indicated that the convection heating feedback can excite not only the CISK–Kelvin wave but also the CISK–Rossby wave in tropical atmosphere. These waves play a very important role in driving tropical ISO (Li 1990; 1993). Recently, some studies have emphasized the importance of nonlinearity in the wave–CISK theory (Lim et al. 1990; Cho et al. 1994; Cho and Li 1999).

The evaporation–wind feedback is advanced as another mechanism to drive the ISO in tropical atmosphere (Emanual 1987; Neelin et al. 1987) and still be introduced into the wave–CISK theory (Li and Liu 1993; Kritman and Vernekar 1993; Crum and Dunkerton 1994). However, further studies show that the evaporation–wind feedback alone is difficult to excite the ISO in tropical atmosphere, because the excited wave propagates too fast. But evaporation–wave feedback can lead to unstable wave, so that the combined effect of the cumulus convection heating and the evaporation–wind feedback can be considered as dynamical mechanism of tropical ISO (Li 1995; Zhao and Liu 1996).

Since some studies have shown that intraseasonal oscillation also exists in the ocean, the air–sea interaction was regarded as a mechanism of tropical atmospheric ISO (Lau and Shen 1988; Hirst and Lau 1990; Li and Liao 1996; Wang and Xie 1998). Exceptionally, the eastward propagation of the coupled wave is only favourable for the oceanic ISO but not for the atmospheric ISO due to its slow propagation.

In this paper, the cumulus convection heating (wave–CISK), the air–sea interaction effect and the evaporation–wind feedback are altogether introduced in a theoretical model, in order to understand their role in driving tropical atmospheric ISO. Any process that can lead the phase speed of wave to be closer to the observed tropical ISO or lead to the unstable wave will be regarded as important mechanism of the tropical atmospheric ISO. Since the structure of tropical ISO, particularly the vertical structure, has been described and explained by the wave–CISK theory very well (Lau and Peng 1987; Li 1988), the structure of excited wave will not be discussed in this study. The consideration of physical processes and the numerical model are given in section 2. Dynamical discussion of the phase speed and instability of the excited wave is given in section 3. The section 5 is the general calculation Results are given in section 4. Section 5 is the conclusions.

2. Model and physics

Generally, the atmospheric governing equations for Kelvin wave on the equatorial beta–plane without basic flow, Rayleigh friction and Newton cooling can be written simply as follows:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = 0 \ , \tag{1}$$

$$\frac{\partial H}{\partial t} + U\frac{\partial H}{\partial x} + D\frac{\partial U}{\partial x} = - Q - EU \ , \tag{2}$$

where the coordinates (t, x) measure time and distance in the eastward direction, U is zonal wind speed, H is the deviation from D (the mean depth of the equivalent atmosphere). In (2), Q is atmospheric diabatic perturbation heating rate; the term EU represents the evaporation–wind feedback, E is a constant.

The atmospheric diabatic perturbation heating Q includes the major internal heating (cumulus convection heating) and the major external heating (the heat flux from the ocean to the atmosphere). The internal heating in the present case can be parameterized as

$$Q_1 = -\eta\frac{\partial U}{\partial x} . \tag{3}$$

where η resembles the heating function as a constant. Based on some studies (Philander et al. 1984; Battisti and Hirst 1989), the heat flux from the ocean to the atmosphere can be parameterized as

$$Q_2 = \alpha(h - \kappa h^3) . \tag{4}$$

where h is the deviation from d (a mean depth of the equivalent ocean); α and κ are coefficients to describe air–sea interaction.

The oceanic model is a one–layer shallow water model driven by the wind and can be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} = \gamma U , \tag{5}$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + (d + h)\frac{\partial u}{\partial x} = 0 , \tag{6}$$

where u is zonal oceanic current speed, the term γU represents the wind stress with γ as stress coefficient. Since the fundamental forcing of the atmosphere on the ocean is wind stress while the fundamental forcing of the ocean on the atmosphere is the heating, only these two key processes are considered in present study for the simplicity.

Obviously, Eqs.(1), (2), (5) and (6) can be regarded as the simplest self–organized system with 4 independent variables. In the positive feedback process, which is defined as atmospheric motion acting on the ocean and the heating from the ocean to the atmosphere, the positive (negative) h will cause atmospheric convergence (divergence) through the effect of term $-\alpha h$. In the meantime, oceanic convergence (divergence) will further enhance positive (negative) h. In the negative feedback process, which is defined as the gravitational restoring force connecting with the stratification of the ocean and the nonlinear term $\alpha\kappa h^3$, the gravitational restoring force in Eq.(5) produces divergence (convergence) in the maximum (minimum) value region of h. The divergence (convergence) then will decrease (increase) the value of h. The nonlinear term also plays certain role in the negative feedback.

In order to obtain the analytic solution, we only discuss the linear case in the present paper. The linearized equations can be written as follows:

$$\frac{\partial U}{\partial t} + g\frac{\partial H}{\partial x} = 0 , \tag{7}$$

$$\frac{\partial H}{\partial t}+(D-\eta)\frac{\partial U}{\partial x}=-\alpha h-EU\ , \tag{8}$$

$$\frac{\partial u}{\partial t}+g\frac{\partial h}{\partial x}=\gamma U\ , \tag{9}$$

$$\frac{\partial h}{\partial t}+d\frac{\partial u}{\partial x}=0\ . \tag{10}$$

They can be written as

$$\alpha\frac{\partial h}{\partial t}=g(D-\eta)\frac{\partial^2 H}{\partial x^2}+gE\frac{\partial H}{\partial x}-\frac{\partial^2 H}{\partial t^2}\ , \tag{11}$$

$$gd\frac{\partial^2 h}{\partial x^2}-\frac{\partial^2 h}{\partial t^2}=-\frac{\gamma d}{D-\eta}\left(\frac{\partial H}{\partial t}+\alpha h\right)\ . \tag{12}$$

Adopting the normal mode method, the solutions of Eqs.(11) and (12) are:

$$(H,h)=(H_0,h_0)e^{i(kx-\sigma t)}\ . \tag{13}$$

Substituting (13) into Eqs.(11) and (12) yields the following relation:

$$[\alpha C_o^2(D-\eta)+\gamma dC_a^2]\sigma^2=g(D-\eta)dk^2(\gamma C_a^2+\alpha C_o^2)-\gamma d\alpha^2C_o^2-igEkd\gamma C_a^2\ , \tag{14}$$

where $C_a^2=gH_0$, $C_o^2=gh_0$.

Since $\sigma=\sigma_r+i\sigma_i$. σ_r and σ_i are respectively the frequency and the growth rate of the perturbation (wave). From the relation (14), σ_r and σ_i can be expressed as:

$$\sigma_i=\frac{gdEk\gamma C_a^2}{2[(D-\eta)\alpha C_o^2+\gamma dC_a^2]\sigma_r}\ , \tag{15}$$

$$\sigma_r=k\sqrt{\frac{g(D-\eta)d(\gamma C_a^2+\alpha C_o^2)-\gamma d\alpha^2C_o^2/k^2+\sqrt{[gd(D-\eta)(\gamma C_a^2+\alpha C_o^2)-\gamma d\alpha^2C_o^2/k^2]^2+(dgE\gamma C_a^2/k)^2}}{2[\alpha C_o^2(D-\eta)+\gamma dC_a^2]}}\ , \tag{16}$$

or

$$\sigma_i=\frac{gdE\gamma C_a^2}{2[(D-\eta)\alpha C_o^2+\gamma dC_a^2]C_x}\ , \tag{17}$$

$$C_x=\sqrt{\frac{g(D-\eta)d(\gamma C_a^2+\alpha C_o^2)-\gamma d\alpha^2C_o^2/k^2+\sqrt{[gd(D-\eta)(\gamma C_a^2+\alpha C_o^2)-\gamma d\alpha^2C_o^2/k^2]^2+(dgE\gamma C_a^2/k)^2}}{2[\alpha C_o^2(D-\eta)+\gamma dC_a^2]}}\ . \tag{18}$$

In expression (16) or (18), only the positive root is selected because the classic atmospheric Kelvin wave should propagate eastwards without the ocean, the heating and the evaporation–wind feedback. It is very clear that the excited wave can be named the CISK–Kelvin like wave, which propagates slower than the classic Kelvin wave due to the convection heating feedback. It is also an unstable and dispersive wave due to the evaporation–wind feedback and the air–sea interaction.

3. Discussion of the special solution

Three special cases are considered here to understand the role of various physical processes.

3.1 *Evaporation–wind feedback alone*

Without the ocean and cumulus convection heating in the atmosphere ($C_o = 0$ and $\eta = 0$), expressions (17) and (18) will give

$$\sigma_i = \frac{gE}{2C_x} \tag{19}$$

and

$$C_x = \sqrt{\frac{gD(1+\sqrt{1+E^2/D^2k^2})}{2}} \equiv C_{XE} \ , \tag{20}$$

$$C_{gXE} = C_{XE} - \frac{gE^2}{2\sqrt{2}k} \frac{1}{\sqrt{gD(Dk+\sqrt{D^2k^2+E^2})}\sqrt{D^2k^2+E^2}} \ . \tag{21}$$

Obviously, the excited wave is unstable and dispersive due to the effect of evaporation–wind feedback. The group speed of the excited wave has same propagating direction as the phase speed but slower than the phase speed ($C_{gXE} < C_{XE}$), because of

$$C_{XE} > \frac{gE^2}{2k\sqrt{2gD(Dk+\sqrt{D^2k^2+E^2})}\sqrt{D^2k^2+E^2}} \ .$$

If the evaporation–wind feedback is eliminated ($E = 0$), the wave will become classic atmospheric Kelvin wave ($\sigma_i = 0$, and $C_{XK} = \sqrt{gD}$). It is a stable and eastward propagating wave with faster speed (about 50–60 m s^{-1}). In general, $C_{XE} = C_{XK}$, the phase speed of wave is very different from that of the observed tropical ISO. Therefore, the evaporation–wind feedback alone is difficult to drive atmospheric intraseasonal oscillation.

Even though the starting equations have some differences, the above mentioned result is consistent with that in previous studies (Kirtman and Vernekar 1993; Li 1995). In this simple dynamical study, the effect of evaporation–wind feedback on instability of the Kelvin wave is shown and its limitation in reducing phase speed of the Kelvin wave is also indicated.

3.2 *Air–sea coupling alone*

Without the convection heating ($\eta = 0$) and evaporation–wind feedback ($E = 0$), the air–sea interaction exists alone, expressions (17) and (18) give

$$\sigma_i = 0 \tag{22}$$

and

$$C_x = \sqrt{\frac{Dgd\gamma k^2 C_a^2 + (Dgk^2 - \alpha\gamma)d\alpha C_o^2}{k^2(d\gamma C_a^2 + D\alpha C_o^2)}} \equiv C_{XAS} \ , \tag{23}$$

$$C_{gXAS} = C_{XAS} + \frac{d\gamma\alpha^2 C_o^2}{k\sqrt{(d\gamma C_a^2 + D\alpha C_o^2)[gDd\gamma k^2 C_a^2 + d\alpha C_o^2(Dgk^2 - \alpha\gamma)]}} \ . \tag{24}$$

The expression (22) means that the coupled wave is stable. The expression (23) shows that the phase speed is related to the wavenumber. Thus the excited coupled wave is a dispersive wave and the group speed shown in (24) has same direction as the phase speed but faster than the phase speed.

Since $(\gamma dC_a^2 + \alpha DC_o^2) = (\gamma dC_a^2 + \alpha dC_o^2 - \gamma d\alpha^2 C_o^2 / gD)$, the relation $C_{XAS} = C_{XK}$ can be obtained when the air–sea coupling is stronger ($\gamma\alpha$ is larger). This means that the stronger air–sea coupling could favour the tropical ISO.

3.3 *Combined effect of cumulus heating and evaporation–wind feedback*

Without the effect of the ocean ($C_o = 0, \alpha = 0$), expressions (17) and (18) give

$$\sigma_i = \frac{gE}{2C_x} \ , \tag{25}$$

and

$$C_x = \sqrt{\frac{g(D-\eta)}{2}[1 + \sqrt{1 + E^2/(D-\eta)^2 k^2}\,]} \equiv C_{XCE} \ , \tag{26}$$

$$C_{gXCE} = C_{XCE} - \frac{gE^2}{\sqrt{8g(D-\eta)k^2[1 + \sqrt{(D-\eta)^2 k^2 + E^2}\,]}\sqrt{(D-\eta)^2 k^2 + E^2}} \ . \tag{27}$$

When the evaporation–wind feedback is omitted ($E = 0$), (26) will represent the atmospheric CISK–Kelvin wave, i.e., $C_{XCK} = \sqrt{g(D-\eta)}$ with $\sigma_i = 0$. In general, $C_{XK} = C_{XCK} = C_{XCE}$, the convection heating feedback is very important to reduce the phase speed of excited wave. Therefore, the cumulus convection heating is mainly responsible for the propagating speed of the excited wave and the evaporation–wind feedback for the instability of the excited wave. These results are consistent with that in previous studies (Li and Liu 1993; Kirtman and Vernekar 1993; Li 1995) even though the starting equations have some differences.

It is very clear that the favourable situation for the tropical atmospheric ISO is the generation of an unstable and dipersive wave, particularly with the phase speed $C_{XCE} = C_{XK}$, through the combined effect of convection heating (wave–CISK) and evaporation–wind feedback.

4. General calculation results

The phase speed of the excited wave in various cases can be calculated through using general parameters in the ocean and atmosphere, that is $C_a = 40$ m s^{-1}; $C_o = 1.5$ m s^{-1}; $D = 250$ m; $d = 0.28$ m; $k = \frac{2\pi}{L}$, where k is wavenumber and L wavelength. The values of parameters E, α, γ and L will be different in different cases.

The result for the case with evaporation–wind feedback alone is shown in Fig. 1. It is obvious that the phase speed (C_{XE}) of excited wave increases very fast with the increase of wavelength. C_{XE} will be greater than 50 m s^{-1} as the wavelength is over 2×10^7 m. It is well known that the wavelength of tropical ISO is usually longer than 2×10^7 m. Therefore, the wave caused by evaporation–wind feedback alone is not consistent with the intraseasonal wave in the tropical atmosphere. In other words, the evaporation–wind feedback alone is difficult to excite tropical ISO in the atmosphere.

The result for the case with combined effect of cumulus heating feedback (wave–CISK) and evaporation–wind feedback is given in Fig. 2, with a moderate intensity of evaporation–wind feedback (fixed $E = 1.5 \times 10^{-5}$). Although, we selected the larger wavelength and equivalent atmosphere depth D and weaker heating intensity, the phase speed

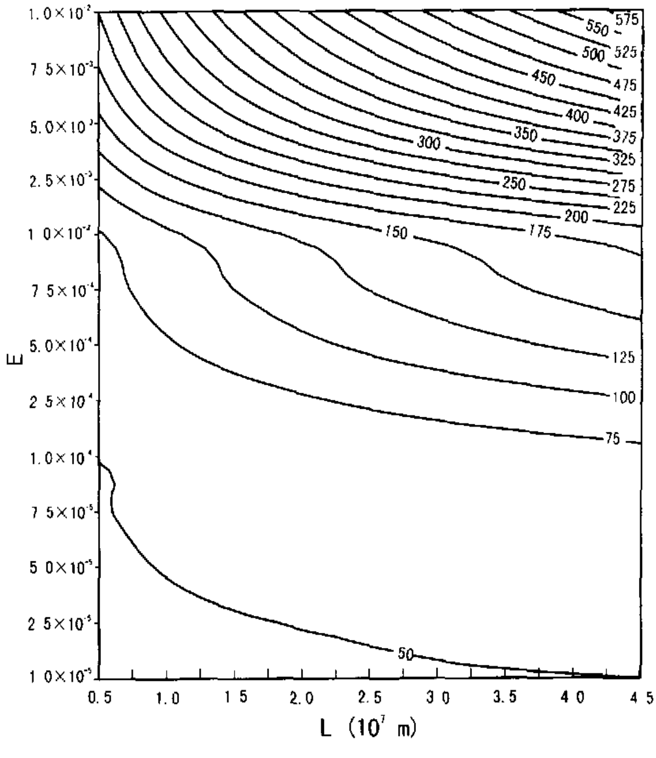

Fig. 1. Relationship between the phase speed of excited wave (C_{XE}) and the parameters (E and L).

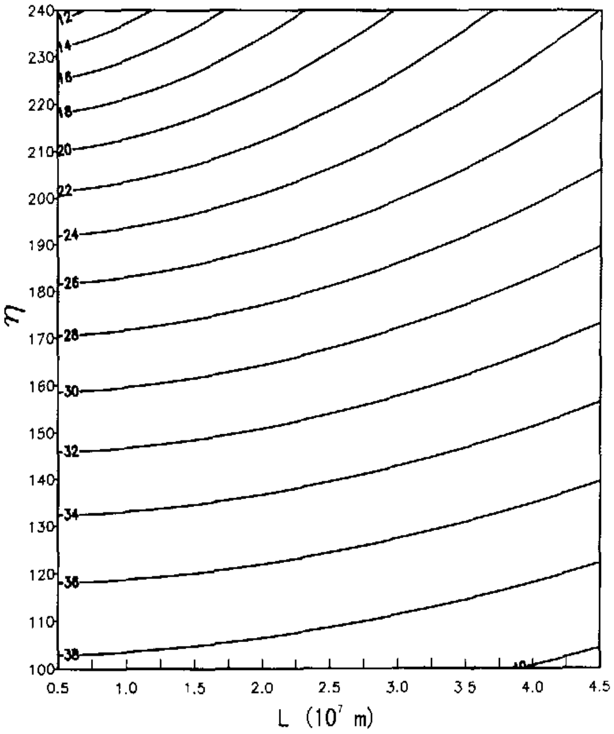

Fig. 2. Relationship between the phase speed of excited wave (C_{XCE}) and the parameters (η and L).

C_{XCE} is still closer to the propagation speed of observed ISO in tropical atmosphere. Therefore, the convection heating feedback (wave–CISK) is very important in exciting the ISO in tropical atmosphere.

The result for the general case is shown in Fig. 3, with stronger heating ($\eta = 150$) and moderate evaporation–wind feedback ($E = 1.5 \times 10^{-5}$). The comparison between Fig. 3 and Fig. 2 reveals that the phase speed of excited wave is reduced further by air–sea interaction. For example, the C_{XCE} is about 30 m s^{-1} as $L = 2.8 \times 10^7$ m and $\eta = 150$ in Fig. 2, but C_x in Fig. 3 is smaller than 20 m s^{-1} generally. It is also clear that the air–sea interaction parameter α is quite important to reduce the phase speed of excited tropical low-frequency waves. It is also evident that the larger γ (stronger wind stress) will quicken the phase speed of excited wave.

Although the group speed C_{gX} is not calculated in this study, the dispersive feature of excited wave has been indicated in above analyses. As we know, the OLR or TBB data are usually used to study the tropical ISO, particularly the propagation of the ISO (Lau and Chan 1985; Knuston and Weickmann 1987). An expansion of cloud cluster can be seen during the propagation of tropical ISO according to OLR or TBB data. This expansion can be regarded as a dispersive phenomenon of the ISO and explained by using the dispersive feature of excited wave with the effects of evaporation–wind feedback and air–sea interaction, because the combined effect of evaporation–wind feedback and air–sea interaction will excite

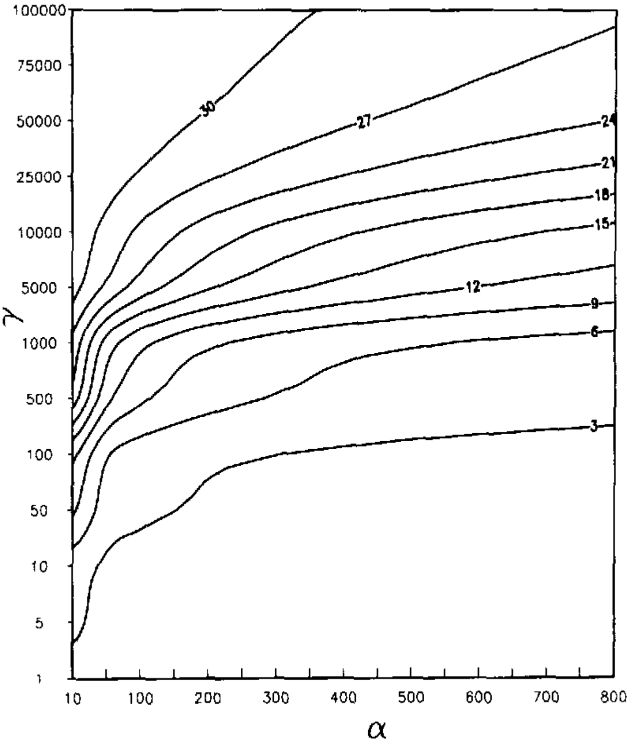

Fig. 3. Relationship between the phase speed of excited wave (C_x) and the parameters (α and γ).

a dispersive wave with the phase speed related to the wavenumber. It is shown that the evaporation–wind feedback will decrease the group speed to be slower than the phase speed of the excited wave but the air–sea interaction will increase the group speed to be faster than the phase speed of the excited wave. The expansion of cloud cluster results from the new generation due to the energy dispersion of the ISO.

5. Conclusion

The important role of wave–CISK, evaporation–wind feedback and air–sea interaction effect in exciting tropical atmospheric ISO is respectively discussed in this paper, theoretically. The result showed that a CISK–Kelvin like wave is excited in the model. This wave propagates eastward slowly as the observed tropical ISO does due to the convection heating feedback and air–sea interaction. It becomes unstable due to the effect of evaporation–wind feedback. It is also a dispersive wave due to the evaporation–wind feedback and the air–sea interaction.

The convection heating feedback (wave–CISK) is the dominant process in reducing phase speed of the excited wave to be closer to the propagation speed of observed ISO (about 10–15 m s^{-1}) in the tropical atmosphere. The stronger air–sea interaction, particularly the oceanic heating also plays certain role in reducing phase speed of the excited atmospheric wave.

Since the existence of instability is a favourable condition for the ISO activity in the tropical atmosphere, the evaporation–wind feedback cannot be omitted as a mechanism of tropical atmospheric ISO despite this feedback alone is difficult to excite the ISO. When there is the combined effect of cumulus heating feedback (wave–CISK) and evaporation–wind feedback, the phase speed of excited wave is closer to the propagation speed of observed ISO (about 10–15 m s^{-1}) in tropical atmosphere. This means that the wave–CISK plays a key role in reducing the phase speed of excited wave and it can be regarded as a fundamental dynamical mechanism of the ISO in tropical atmosphere.

The evaporation–wind feedback and air–sea coupling interaction will excite a wave with the phase speed related to the wavenumber. Therefore, the excited wave has dispersive feature due to the effect of evaporation–wind feedback and air–sea coupling interaction.

This study is partly supported by National Key Programme for Developing Basic Sciences (G1998040903)

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有蒸发-风反馈和海-气相互作用的CISK开尔文波——热带季节内振荡机制的进一步研究

李崇银　　禚汉如　　王作台

摘　要

P4　A

将波动-CISK(积云对流加热反馈).海-气相互作用和蒸发-风反馈都引入一个简单理论模式，研究了它们在驱动热带大气季节内振荡(ISO)中的作用。其结果表明，波动-CISK在减慢激发波的位相速度以接近观测到的热带ISO的移速过程中起主要作用；而蒸发-风反馈的主要作用是使激发波不稳定；海-气相互作用在减慢激发波的移速方面也有一定作用。因此，波动—CISK和蒸发-风反馈可认为是热带ISO的主要动力学机制。本研究还表明，由于蒸发-风反馈和海-气相互作用的影响，激发波是一种频散波，这种频散性可以更好地解释热带大气中ISO的活动特征。

关键词：季节内振荡，CISK开尔文波，蒸发-风反馈，海-气相互作用