A Critique of Wave-CISK as an Explanation for the 40–50 Day Tropical Intraseasonal Oscillation

By Winston C. Chao

Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland, 20771 U.S.A.

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Abstract

The two major difficulties, *i.e.*, the excessive speed and the smallest preferred scale, encountered by wave-CISK as an explanation for the 40–50 day tropical intraseasonal oscillation (or the Madden-Julian oscillation, MJO), as demonstrated in many studies, are examined. In addition, wave-CISK is contrasted with a more promising framework for interpreting MJO recently proposed by Chao and Lin. The central cause for the two difficulties can be attributed to the convective heating formulation used. Also, depending on how one defines it, the wave-CISK concept as the foundation for interpreting MJO is at best inadequate and at worst erroneous.

1. Introduction

Since its discovery the tropical intraseasonal oscillation of 40–50 day period, also known as the Madden-Julian oscillation (MJO) (Madden and Julian, 1971, 1972; Madden, 1986; Murakami and Nakazawa, 1985; among others), has been a focus of intense interest (for a recent review of MJO observations, see Madden and Julian, 1993). A popular foundation for interpreting MJO in the recent years has been the wave-CISK mechanism (Chao, 1987; Lau and Peng, 1987; Miyahara, 1987; Hendon, 1988; Chang and Lim, 1988; Wang, 1988; Kirtman and Vernekar, 1993; and Blade and Hartmann, 1993). Wave-CISK as an explanation of MJO has two major flaws. One is the problem of its rendering too high eastward speed. Most wave-CISK type simulations yield a period of 20–30 days for the convective region to circle the earth (*e.g.*, Lau and Peng, 1987). To lengthen the period of the oscillation, some studies lowered the height of the maximum cumulus heating to the lower troposphere (Takahashi, 1987; Lau *et al.*, 1989; Sui and Lau, 1989), in disagreement with observations. With such change the wave-CISK type studies can manage to lengthen the period to 40–50 days. However, these studies obtained a precipitation region circling the whole globe in 40–50 days (*e.g.*, Figs. 2 and 5 of Blade and Hartmann). This result is in conflict with the observations. The precipitation region associated with the MJO moves only from the Indian Ocean to mid-

Pacific, a third of the globe where SST is relatively high, in about 40–50 days (and is followed by a new convective region starting in the Indian Ocean), a much slower speed (see the cover picture of Bulletin of AMS, May 1986, by Lau and Chen). This fact raises serious doubts about the wave-CISK mechanism as a valid explanation for MJO. The circulation fields associated with the moving convective region have a global scale component, which has of course the same period. Thus when the circulation fields alone are analyzed (particularly the 200 mb streamfunction), one gets an incomplete picture of a global scale traveling mode circulating the whole globe with a 40–50 day period. The essence of MJO is the successive convective regions traveling across only one third of the globe with a period of 40–50 days. To explain MJO requires understanding the origin of these convective regions and their propagation speed.

The other serious problem with the wave-CISK mechanism is that its most favored scale of the convective region is the smallest scale in a model or zero in analytic studies (Lau and Peng, 1987; Hendon, 1988; Kirtman and Vernekar, 1993; and Blade and Hartmann, 1993). The model results may not show exactly grid-scale precipitation region due to horizontal diffusion, but the precipitation area has very small size. Attempts to resolve this difficulty (*e.g.*, Wang and Chen, 1989; Wang and Rui, 1990) have not been validated in models. However, we should point out that the scale selection problem exists mostly in linear models (with or without con-

ditional heating) and some nonlinear (*i.e.*, the model dynamics contains the complete advective terms) models do not have this problem (Hayashi and Sumi, 1986). But in these nonlinear models there are a large number of small convective regions (*e.g.*, Fig. 3 of Numaguti and Hayashi, 1991), contrary to what is observed.

The evaporation-surface wind feedback mechanism, later renamed as the wind-induced surface heat exchange (WISHE) mechanism (Emanuel, 1987; Neelin *et al.*, 1987), is not a strong contender in capturing the essence of MJO, although it must have some modifying roles. Neelin *et al.* (1987) showed that when WISHE is suppressed in their model the same MJO-like oscillation can still occur but with weaker amplitude.

Recently Chao and Lin (1994, hereafter CL) proposed a more promising framework for interpreting MJO, in which MJO is depicted as a result of successive convective regions of size 5,000–10,000 km moving eastward starting from the Indian Ocean and ending in mid-Pacific in about 40–50 days. Such convective region is composed of one or more super cloud clusters. The origin of the super cloud clusters (of size 2000–4000 km) is attributed by CL to the cloud cluster tele-induction mechanism of a new cloud cluster induced by the existing cloud cluster which subsequently terminates. The successive generation of new cloud clusters on the upstream side (the side that the basic flow is from) of the existing ones and the demise of the latter form an envelope which is the super cloud cluster. One or more super cloud clusters form the convective region that moves eastward and drives the MJO. The CL interpretation is consistent with the recent observational findings (Nakazawa, 1988; Lau *et al.*, 1991; Sui and Lau, 1992). In this work we will examine the results of the wave-CISK type MJO studies (Section 2) in detail and try to interpret their characteristics. We will then compare wave-CISK with the CL interpretation (Section 3). Such comparison will help us in understanding the cause(s) for wave-CISK's failure in interpreting MJO. A summary of our discussion is presented in the final section.

2. Characteristics of wave-CISK type MJO studies

The term CISK (conditional instability of the second kind) has been used by different authors to mean quite different concepts (For a critical discussion on CISK, see Ooyama 1982.) Here we will confine ourselves to its original meaning, *i.e.*, the cooperation between convective heating and the heating induced low level moisture convergence through surface friction. It is a common knowledge that CISK has been the mechanism proposed for the interpretation of the intensification of tropical cyclones but not necessarily for the initiation of the incipient tropical

cyclones. The term wave-CISK means that the low level convergence through surface friction in CISK is replaced by convergence of the wave (or the circulation field) excited by the convective heating. Almost all tropical phenomena that depend on convection for their energy supply have some kind of cooperation between convection and circulation and can fall under the umbrella of wave-CISK. Thus it is not surprising that when the wave-CISK concept was first introduced by Hayashi (1970) and Lindzen (1974) it was used as the foundation of investigating numerous tropical phenomena, including easterly waves, Rossby waves, Yanai waves, Kelvin waves, tropical cyclones, *etc.* Naturally when the MJO investigation started, wave-CISK soon became a popular concept for the investigation. Of course when a basic concept like wave-CISK is being used in such all encompassing manner, one has to be very careful about its validity. Obviously, even in the event that wave-CISK is proven valid, it alone cannot possibly explain so many tropical phenomena. Additional mechanisms unique to individual phenomena must be invoked in conjunction with wave-CISK to arrive at a full explanation. In this paper we concentrate on one phenomenon-MJO-only and examine the validity of wave-CISK in explaining it.

Wave-CISK, when used in analytical or simplified numerical studies, requires a quantitative method of relating convective heating to atmospheric circulation. The most popular method of formulating such relation is $Q = \eta(p)w$, where Q is the heating rate per unit mass, w is the vertical velocity at the top of the boundary layer and $\eta(p)$ is a fixed vertical heating profile (There are other factors in this formula; but for simplicity we can assume that they are absorbed into $\eta(p)$). This relation is applied only when w is positive, the so-called conditional heating. Unconditional heating is rather unrealistic and is thus not considered. In this paper the basic concept of wave-CISK plus this simple heating formulation will be referred to as wave-CISK+ Q_{wf} , where the subscript wf is a reminder for that the heating formula has two important characteristics: dependence on w and a fixed vertical profile. In nearly all wave-CISK studies of MJO the formulation for the dynamics part of the investigation is not in question. (Although it is not certain if linear dynamics suffices.) The difficulties encountered in these studies are mainly related to the convective heating formulation.

The first common difficulty with wave-CISK + Q_{wf} in explaining MJO is that the convective region generated in models with Q_{wf} (*i.e.*, the region with precipitation) moves too fast (at a speed about three times as the observed). Its speed is close to that of the Kelvin wave (the first baroclinic mode) and the associated circulation field has a dominant internal Kelvin wave component. This

led to the popular belief, for some years in the course of the MJO investigation, about MJO being a Kelvin wave-CISK phenomenon. In fact observations show an important though weaker Rossby wave component (Nogue-Paegle *et al.*, 1990; Salby and Hendon, 1993). The reason for the near Kelvin wave eastward speed in models with Q_{wf} has to do with the wave-CISK heating formulation. As shown by Chao (1987) and Yamagata (1987) using Gill's model (1980) and his "long-wave approximation", with linear dynamics, the low level convergence induced by a prescribed convective heating pattern is the largest when this convective heating region travels eastward in a resting basic flow with a speed close to, but less than, that of the Kelvin wave and this feature persists in their model if the longitudinal heating domain is small, say 500 km instead of 2000 km. The fact that the smaller scales are preferred is discussed shortly. Also there is a secondary local maximum convergence at a speed close to, but greater than, that of the Rossby wave. Figure 1 shows the convergence as defined in Chao (1987) as a function of the speed of the prescribed heating. (An addition to Chao's solution is given in Appendix A.) These are consistent with the fact that in Lau and Peng's (1987) experiments the final steady state is a convective region moving at near Kelvin wave speed and in the initial transient stage there are, in addition to the Kelvin wave components, Rossby wave components moving westward. Most wave-CISK type model simulations use a grid size of about 5° or larger so that even the smallest convective region can be considered under Gill's long wave approximation and the gravity waves can be disregarded when studying the model results. Thus the near Kelvin wave speed of the wave-CISK+ Q_{wf} results can be interpreted as the optimal speed for boundary layer convergence. The different stability anomalies on the east and the west sides of the precipitation region obtained in models with nonlinear dynamics (*e.g.*, Hendon, 1988) can at best be a minor factor in the interpretation of the eastward movement, in view of the fact that the Lau and Peng experiments, which gave essentially the same results, were done with linear dynamics. Another possible, but minor, factor that contributes to the fast eastward speed in the wave-CISK results, at least in models with nonlinear dynamics, is that fast moving convective region can best garner the moisture supply in the boundary layer and the Kelvin wave speed is the fastest speed that the convective region can attain. Chao (1987) and Yamagata (1987) showed that if the prescribed convective region travels at a speed much slower than the Kelvin wave speed the induced circulation has a sizeable Rossby wave component, a picture more consistent with the observations. Thus the wave-CISK+ Q_{wf} mechanism cannot possibly be used to explain the speed of the

Fig. 1. The nondimensional low level convergence, as defined in Chao (1987), induced by a prescribed heating region with longitudinal nondimensional size $L = 0.5$ (about 600 km) and dissipation rate $\varepsilon = 0.2$ (or, 10^{-6} s^{-1}) moving with a nondimensional speed C_0 . $C_0 = 1$ and $C_0 = -1/3$ are the speeds of the Kelvin wave and Rossby wave, respectively. See Chao (1987) for notations.

convective region associated with MJO.

The second common difficulty with wave-CISK+ Q_{wf} is the scale selection problem, *i.e.*, the scale of the convective region obtained in these studies is that of the grid size in finite difference models with linear dynamics and the growth rate approaches infinity as the scale approaches zero in analytic studies. If the horizontal diffusion is sufficiently large, the size of the convective region can be greater than the grid size. This problem has been discussed in many recent studies (Yoshizaki, 1992; Crum and Dunkerton, 1992; Wang and Xue, 1992). An alternative way of understanding this problem is through the example of cumulus convection where the most unstable mode has the smallest size (Bjerknes, 1938). The detailed explanation is given in Appendix B. Also, in models with linear dynamics the mode with a single convective region in the whole globe is the most unstable one. However as mentioned in the introduction in some models with nonlinear dynamics the number of convective regions is too numerous as compared to the observations. The reason that other models with nonlinear dynamics result in a single convective region in the entire domain (*e.g.*, Blade and Hartmann, 1993) remains unclear.

The phase-lagged wave-CISK (Davies, 1979) has some observational support in that the convective heating is better correlated to a phase-lagged boundary layer convergence. It manages to avoid the scale selection problem. However the size of the

time lag is determined empirically and is difficult to justify. The improvements the phase-lagged wave-CISK achieved are overshadowed by the loss of the high degree of balance between diabatic heating due to cumulus convection and adiabatic cooling due to large-scale ascent (Davies, 1979). Also the growth rate of the most unstable modes is relatively small. Cho *et al.*'s (1994) study also employed the phase-lagged wave-CISK. Their results cannot account for the fact that the convective region associated with MJO travels only one third of the globe in about 40–50 days.

There is an additional difficulty with wave-CISK in that in the wave-CISK+ Q_{wf} solution the precipitation region is quasi-steady traveling at a constant speed, whereas the observed precipitation region is composed of wave packets with envelope waves (the super cloud clusters) and carrier waves (the cloud clusters with a life span of 2–3 days) (Nakazawa, 1988). The reason for this unrealistic result of the wave-CISK+ Q_{wf} type simulation will be made clear in the following section.

3. Comparison of wave-CISK with the super cloud clusters forcing interpretation

The CL simulations indicate that to simulate MJO successfully one must be able to simulate the super cloud clusters, which are the driver of MJO. And the successful simulation of the super cloud clusters entails the simulation of the life cycle of individual cloud clusters and the cloud cluster tele-induction mechanism of generating a new cloud cluster on the upstream side of an existing cloud cluster. During the life cycle of a cloud cluster the vertical heating profile undergoes a drastic change. When a cloud cluster first emerges the heating is limited to the lower troposphere. As the cloud cluster matures the maximum heating level moves upward and in the mature stage there is convective cooling in the lower troposphere. The associated sudden upward motion in the resolvable scales sets off gravity waves propagating both upstream and downstream. Since the moisture field is not symmetric on the two sides of the cloud cluster with the upstream side having more moisture (simply because the moisture on the upstream has not been used by the cloud cluster), gravity wave (the model used by CL has neither f nor β) can set off a new cloud cluster more easily on the upstream side. Occasionally the convective cooling in a cloud cluster drives a meso-scale downward motion which forces the boundary layer air to move both upstream and downstream. The upstream branch creates a convergence on the upstream side of the existing cloud cluster. The boundary layer convergence, combined with the high moisture content on the upstream side, initiates a new cloud cluster. Once a new cloud cluster is generated, it competes for moisture supply with the ex-

isting one and leads to the demise of the latter. The successive formation of new cloud clusters on the upstream side and the downstream movement and the demise of the existing ones give rise to an envelope which is the super cloud cluster. The heating formulation in the wave-CISK+ Q_{wf} , with a time-independent vertical profile, is obviously not up to the task of simulating the life cycle of cloud clusters; let alone the cloud cluster tele-induction mechanism. As shown by CL even some more sophisticated convection schemes failed to simulate the life cycle of the cloud clusters and rendered results very similar to those of wave-CISK+ Q_{wf} . According to the CL interpretation the super cloud cluster is the manifestation of a kind of nonlinear cloud cluster instability and the convection scheme must have the ability to simulate the instability that is responsible for the starting of a new cloud cluster. Q_{wf} obviously fails in this regard, judging from the fact that the resultant cloud clusters persist.

Then, there is the question of whether the basic wave-CISK concept still plays any role, perhaps in the origin of cloud cluster. In our view in the CL simulations where convection is parameterized, the basic wave-CISK concept appears to be operating at the scale of cloud cluster. Of course when the convective region associated with MJO is viewed as a whole, there is heating in this entire region and convergence into it in the boundary layer giving the appearance of wave-CISK. However these have only the significance of appearance and the basic wave-CISK concept is inadequate in providing any foundation for interpreting MJO or cloud cluster.

Wave-CISK+ Q_{wf} , as a concept, operates at the cloud scale only (as can be argued through the Bjerknes type of explanation. Also, we do not imply that wave-CISK+ Q_{wf} is a good way of simulating individual clouds. Obviously the individual cloud has its own life cycle and its associated vertical heating profile is not time independent.) Thus Ooyama's (1982) remark "...but many papers of so-called CISK theory are discussing convective clouds in disguise" is in accordance with our view. The wave-CISK associated with a cloud cluster is only an appearance. Like the super cloud clusters which originate from the nonlinear interaction among cloud clusters, cloud clusters depend on the nonlinear interaction among clouds; *i.e.*, the initiation of a cloud depends on the circulation field associated with existing clouds. Thus wave-CISK+ Q_{wf} when used as the foundation to explain MJO, in attempting to relate planetary-scale circulation directly to cumulus ensemble heating, fails to address the nonlinear scale-interaction of a spectrum of tropical phenomena (the whole convective region associated with MJO, super cloud clusters, cloud clusters, and individual clouds) and the nonlinear interaction among entities of the same scale that are responsible

for the origin of many tropical phenomena (MJO, in particular). Therefore, unsurprisingly, studies of MJO based on wave-CISK concept encountered problems.

4. Remarks and Summary

We agree that the basic idea of wave-CISK, *i.e.*, the cooperation between convection and convection induced circulation, does appear in MJO, as in many other tropical phenomena. However, we have argued that this basic concept of wave-CISK is far from adequate in capturing the essence of MJO; any tropical phenomenon that depends on convection for its energy supply has wave-CISK operating in it. We advocate that the essence of MJO lies in the origin of the super cloud cluster, which owes its origin to the cloud cluster tele-induction mechanism. This mechanism allows the generation of a new cloud cluster on the upstream side of an existing cloud cluster. The competition for moisture supply between the new and the existing cloud clusters is lop-sided in favor of the new cloud cluster. The decay of the existing cloud clusters and successive generation of the new ones create an envelope, which is the super cloud cluster, normally moving eastward. So the nonlinear nature of the super cloud cluster, as manifested in the interaction between cloud clusters, is evident. The role of the basic flow has been mentioned in CL and will be further expounded in a forthcoming paper.

We have interpreted the behavior of the results of the wave-CISK type of MJO studies. And through a comparison with CL, we have found that the central cause for the failure of wave-CISK+ Q_{wf} in capturing the essence of MJO lies in the formulation of the convective heating Q_{wf} . The simplicity of the fixed vertical heating profile forbids the proper simulation of the life cycle of cloud clusters which includes the explosive rise of the convective mass and/or meso-scale downward flux that trigger the generation of a new cloud cluster. As demonstrated in CL with better treatment of convective parameterization, the super cloud clusters, which drives MJO, can be simulated. As mentioned in CL in the successful simulation and in nature wave-CISK, as an instability mechanism, is not operating at the whole convective region scale as conceptualized in the wave-CISK MJO studies. Moreover, the successful simulation of MJO depends on the successful simulation of the super cloud clusters, which in turn depends on the successful simulation of the life cycle of the cloud clusters and the cloud cluster tele-induction mechanism (thus resolving cloud clusters in the model is essential). Once the latter point is clear, there can be no doubt about the importance of cumulus parameterization scheme in any attempt to simulate MJO, unless a cloud resolving model is used.

In summary, our criticism of wave-CISK as a foun-

ation for the interpretation of MJO is that the basic concept of wave-CISK, defined as the cooperation between convection and convection induced circulation, is valid; but it is *inadequate*. One needs a cumulus parameterization in order to do any simulation (unless of course ones uses a cloud resolving model) or any analytic study. If the chosen cumulus parameterization is Q_{wf} , one ends up with *erroneous* results. Even when a good cumulus parameterization or a cloud resolving model is used and one manages to get the super cloud cluster structure and a proper simulation of eastward movement of the convective region, the basic concept of wave-CISK alone is still inadequate in offering a complete explanation of MJO. One needs, in addition, the cloud cluster tele-induction mechanism to explain why the convective region (composed of one or more super cloud clusters) moves eastward at the observed speed. We hope that with this paper we can close the wave-CISK+ Q_{wf} chapter in the investigation of MJO and turn to the new chapter of super cloud clusters, cloud clusters and, above all, cumulus convection schemes.

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Appendix

A. An addition to Chao's (1987) solution

The solutions provided by Chao (1987) and Yamagata (1987) are valid only for $-1/3 < C_0 < 1$. For $C_0 > 1$, q_2 remains the same but q_0 should be changed to:

$$[k^2(1 - C_0)^2 + \varepsilon^2] q_0 = k(1 - C_0) \left\{ 1 + \exp \left[\frac{2\varepsilon L}{1 - C_0} \right] \right\} \exp \left[\frac{-\varepsilon}{(1 - C_0)}(x + L) \right], \quad \text{for } x < -L$$

$$-\varepsilon \cos(kx) - (1 - C_0)k \left[\sin(kx) - \exp \left\{ \frac{-\varepsilon}{(1 - C_0)}(x - L) \right\} \right], \quad \text{for } |x| < L$$

$$0, \quad \text{for } x > L,$$

and for $C_0 < -1/3$, q_0 remains the same but q_2 should be changed to:

$$\begin{aligned}
& [k^2(1+3C_0)^2+9\varepsilon^2]q_2 = \\
& 0, \quad \text{for } x < -L \\
& -3\varepsilon \cos(kx) + (1+3C_0)k \left[\sin(kx) \right. \\
& \left. + \exp \left\{ \frac{3\varepsilon}{(1+3C_0)}(x+L) \right\} \right], \quad \text{for } |x| < L \\
& (1+3C_0)k \left\{ 1 + \exp \left[\frac{6\varepsilon L}{1+3C_0} \right] \right\} \\
& \times \exp \left[\frac{3\varepsilon}{(1+3C_0)}(x-L) \right], \quad \text{for } x > L,
\end{aligned}$$

All notations follow those of Chao (1987).

B. An alternative explanation for the smallest preferred scale in wave-CISK + Q_{wf}

The fact that wave-CISK + Q_{wf} prefers the smallest scale in a model can be explained in a way very closely following the approach taken by Bjerknes (1938) in considering the preferred scale of saturated-adiabatic ascent in a dry-adiabatically descending environment. There is a difference between the case we are considering under wave-CISK + Q_{wf} and the case that Bjerknes considered for the moist convection in that in wave-CISK + Q_{wf} the ascending air does not follow the moist adiabat. However, this is only a minor difference and it affects neither the deduction nor the conclusion. In our case the ascending region means the region where large-scale (or model resolvable scale) vertical motion is upward and convective heating exists. We will follow the simplifications made by Bjerknes and assume that at a given level the ascending air has a uniform density ρ' and its upward (positive) velocity v'_s is uniform over its entire area S' . Similarly the density and the downward (negative) velocity are uniform in the domain of the surrounding descending air S . Thus the balance of mass fluxes requires:

$$\rho'v'_sS' = -\rho v_sS$$

We will denote ρS as m , and thus $m'v'_s = -mv_s$. The local change of temperature in the ascending area and in the descending area are respectively,

$$\partial T'/\partial t = -v'_sP + Q_{wf}/C_p \quad (1)$$

$$\partial T/\partial t = -v_sP$$

where $P = \frac{\bar{T}}{\theta} (d\bar{\theta}/dz)$ and the overbarred quantities are horizontal averages over both ascending and descending regions. We have assumed as Bjerknes did that the static stabilities in the two regions are the same. Although this assumption is valid only initially, it is largely correct for our purpose. By

our definition of wave-CISK + Q_{wf} , Q_{wf} is equal to $\eta(p)w'$ where w' is the vertical velocity at the top of the boundary layer in the ascending region and $\eta(p)$ is the prescribed fixed vertical heating profile. The total heating per second at this level is then:

$$\begin{aligned}
& C_p(m\partial T/\partial t + m'\partial T'/\partial t) = \\
& C_p(m + m')\partial T/\partial t + C_pm'(\partial T'/\partial t - \partial T/\partial t),
\end{aligned}$$

which is equal to $m'Q_{wf}$. The first term on the right hand side is called by Bjerknes the "uniform heating" and the second term the "surplus heating" of the convective region part. It is the surplus heating that is available for the kinetic energy generation and the growth of the convective circulation. We will set the ratio between w' and v'_s to be λ ; i.e., $w' = \lambda v'_s$. Thus the ratio between the uniform heating and the total heating is:

$$C_p(1 + m'/m)P/(\eta\lambda). \quad (2)$$

Thus to minimize this ratio or, equivalently, to maximize the kinetic energy generation, the smaller m' is the better. Thus wave-CISK + Q_{wf} prefers the smallest scale, assuming $\rho \approx \rho'$. This conclusion depends on, of course, that λ does not depend on m'/m or at least it does not decrease as fast as m'/m decreases. We follow the way Bjerknes treated this point and simply assuming λ to be unity, i.e., v'_s being independent of height.

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Wave-CISK による熱帯の 40–50 日季節内振動の説明に対する批判

Winston C. Chao

(Laboratory for Atmospheres, NASA/Goddard Space Flight Center, U.S.A.)

熱帯の 40–50 日季節内振動 (Madden-Julian 振動-MJO) を wave-CISK で説明しようとする二つの問題—早すぎる伝搬と小さいスケールが卓越すること—に直面するが、ここではこの問題について調べた。wave-CISK の結果は最近 MJO を解釈するために提案された Chao-Lin (1994) とは違っている。二つの問題は wave-CISK の対流の熱源の定式化に起因する。それをどう定義するかによるが、MJO を解釈するには wave-CISK は一般に不適切である。