Fundamental Dynamics of the Tropical Intraseasonal Oscillation

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1. Introduction

The tropical intraseasonal oscillation (ISO) is the dominant mode of the global intraseasonal variability with a time scale ranging from two weeks to less than a season. The major mode of the ISO is the Madden-Julian Oscillation (MJO), which has a time scale of typically 40-50 days and is produced by equatorial eastward propagating convection and circulation anomalies (Madden-Julian 1971, 1972). The MJO is most active from November to May. The ISO also includes other modes of variability such as the northward propagating (Yasunari 1979) and the off-equatorial westward propagating (Murakami 1980) oscillations that prevail from May to October in the Asian-Pacific monsoon region.

Accurate modelling and predicting of the ISO may improve seasonal-to-interannual climate prediction, thus bridging the gap between weather forecasting and short-term climate prediction. Unfortunately, current global circulation models have great difficulty in simulating the statistical properties of the ISO because the ISO involves complex interactions among numerous physical processes on different scales of motion. Modelling the ISO entails a series of interacting parameterizations including moisture transport, evaporation, cloud and convection, and radiation transfer. Uncertainties in the mathematical descriptions of these interactive parameterizations could jeopardize a model's capability in simulating the ISO. To make progress, we must fully understand the mechanisms underlying these complex interactions. Particularly important is to come to understand the fundamental dynamics of the ISO.

In the last two decades, numerous studies have been devoted to developing a theoretical understanding of the MJO. The theories in these studies present a broad range of processes and feedback mechanisms, which are summarized into the following categories. (1) Wave convergence-convection interaction (a.k.a., wave-CISK) (e.g., Lau and Peng 1987, Hendon 1988); (2) Wind-evaporation feedback or wind-induced surface heat exchange (WISHE) (e.g., Emanuel 1987, Neelin et al. 1987); (3) Frictional moisture-convergence feedback (e.g., Wang 1988, Wang and Rui 1990, Moskowitz and Bretherton 2000); (4) Cloud-radiation feedback (Hu and Randall 1994a,b, Raymond 2001). In addition, the discharge-recharge mechanism and water-vapor feedback (e.g., Blade and Hartmann 1993, Grabowski 2003), the impacts of tropical seasonal mean circulation (Wang and Xie 1997), and ocean mixed-layer feedback (e.g., Flatau et al. 1997, Wang and Xie 1998, Waliser et al. 1999) have all been shown to play significant roles in the ISO in general, and in the MJO in particular.

While substantial progress has been achieved, various aspects of these theories remain disputable and incomplete. In this paper, an idealized model is presented that hopefully identifies the essential physics of the ISO and provides a unified theoretical framework to explain the complex behaviour of the ISO. A series of theoretical studies using this model were conducted, and based upon these simulations the fundamental dynamics of the MJO and monsoon ISO are elucidated and discussed.

2. The theoretical model

The aim of the theoretical model presented here is to establish a simple, unified framework for studying the ISO. It is a time-dependent primitive equation model on an equatorial beta-plane that consists of a two-level free troposphere and a well-mixed planetary boundary layer. Figure 1 highlights the essential model physics, which focus on the nonlinear interactions among condensational heating, low-frequency equatorial waves, boundary layer moist dynamics, and wind-induced heat exchanges at the surface. This nonlinear interaction will be called, for short, "convective interaction with dynamics" (CID), following Neelin and Yu (1994). The model also includes the impacts of mean flows and mean specific humidity (a function of SST) and the effect of the interactive SST feedback to CID. Thus, the model physics integrate, to various degrees, all of the mechanisms listed in the review above except for cloud-radiative feedback.

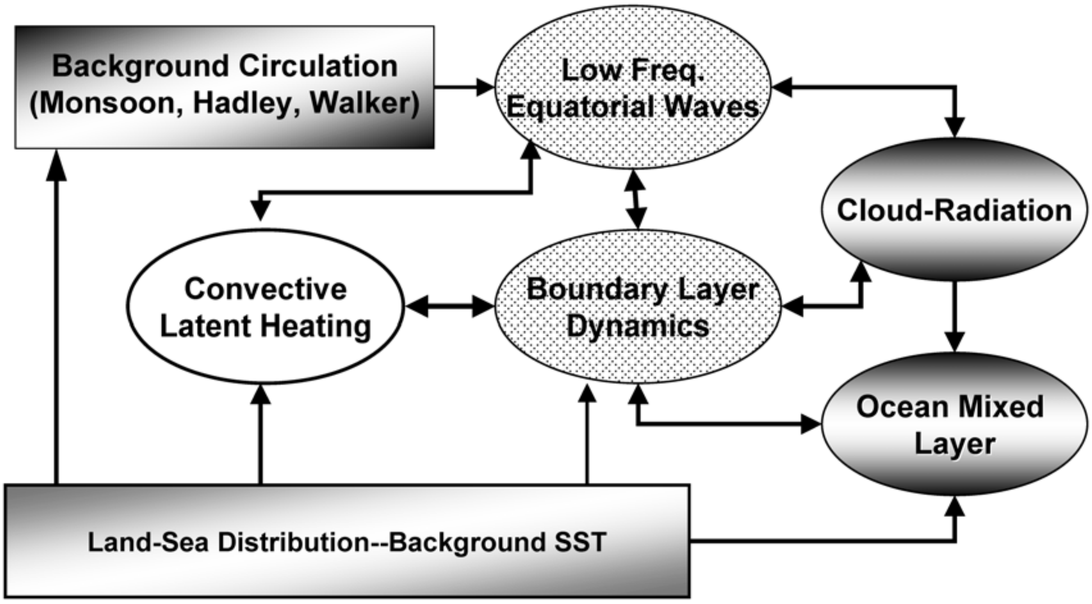

Figure 1 The essential physics in a theoretical model for simulating the tropical ISOs

What are the fundamental characteristics of the MJO and tropical ISO in general that a theory must explain? Given the complexity of the phenomenon and observational limitations, selecting these features is a difficult task. Nevertheless, such a list is necessary for model validation, and the following set of statistical features is proposed: (1) intraseasonal timescale (30 – 60 days); (2) planetary scale zonal circulation coupled with a large-scale convective complex (Madden and Julian 1972); (3) a baroclinic circulation structure with boundary layer convergence preceding the major precipitation (Hendon and Salby 1994, Sperber 2003); (4) a horizontal circulation pattern comprising equatorial Kelvin and Rossby wave components (Rui and Wang 1990); (5) slow eastward propagation (about 5 ms^{-1}) in the eastern Hemisphere (Knutson and Weickman 1986); (6) longitudinal dependence for amplification and decay of the disturbance (Wang and Rui 1990b); and (7) remarkable seasonality, especially the prominent northward propagation (Yasunari 1979) and off-equatorial westward propagation (Murakami 1980) in the Asian monsoon region during the summer monsoon. More stringent validation characteristics might include the multi-scale structure of the convective complex (Nakazawa 1988) and the coupling with SST variability (Krishnamurti et al. 1988).

Regardless of its simplicity, the model is able to reproduce intraseasonal modes that resemble closely the above features of the observed MJO and monsoon ISO. The fact that the model ISO is realistic implies that the essential physics represented by the crude parameterizations within the model are also reasonably realistic and sufficiently useful for providing insights into the fundamental dynamics of ISO.

3. Mechanism of the MJO

Linear theory suggests that these low-frequency disturbances may originate from the fastest growing frictional CID mode, which propagates slowly eastward (5-10 m/s) with the growth rate on intraseasonal time scale (about 10^{-6} s^{-1}) (Wang and Rui 1990). The growth rate increases with increasing zonal wavelength. The structure of the growing mode is characterized by a coupling between an equatorial Kelvin wave and the most trapped equatorial Rossby wave. A basic feature is that the frictional convergence in the boundary layer is located east of the major precipitation region by a fraction of the wavelength. The characteristic structures are shown in the schematic diagram Figure 2.

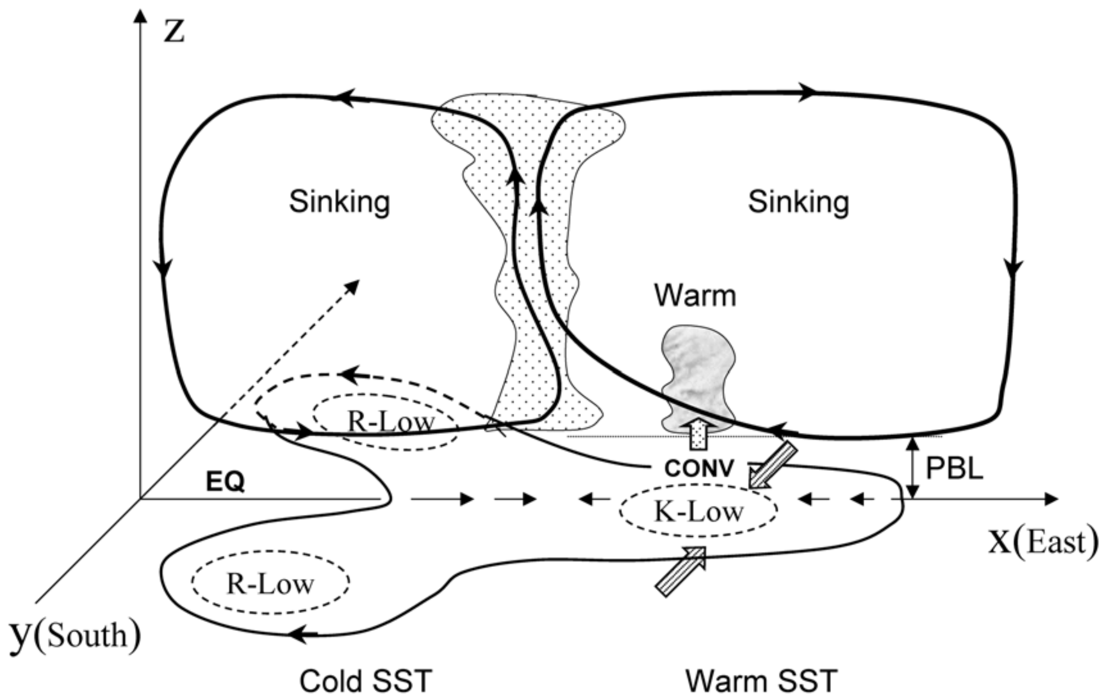

Figure 2 Schematic vertical and horizontal structures of the model MJO. In the horizontal plane the 'K-low' and 'R-low' represents the low-pressure anomalies associated with the equatorial Kelvin and Rossby waves, respectively. Arrows indicate the wind directions. In the equatorial vertical plane the free tropospheric wave motion is highlighted. The wave-induced convergence is in phase with the major convection, whereas the frictional moisture convergence in 'K-low" region is ahead of the major convection.

Analysis of the simulations with the model described above helps to elucidate the basis dynamics of the low-frequency disturbances that produce the MJO. The model results show frictional moisture convergence in the boundary layer, which links the surface heat exchange, free tropospheric waves, and condensational heating, plays a vital role in developing the low frequency frictional CID mode. There are a number of key questions that a theory should address and the answers in terms of the model analysis are as follows.

(i) Why does convergence in the boundary layer precede the major rising motion and precipitation? It can be shown that in a Kelvin wave the upward motion is located in its low pressure. The deep convective heating stimulates eastward propagating equatorial Kelvin waves that form a pressure trough east of the convection, thereby fostering meridional wind convergence (Figure 2).

(ii) How does frictional convergence hold the Kelvin and Rossby waves together and select eastward propagation? For the most trapped equatorial Rossby wave, the upward motion occurs in both the off-equatorial low pressure and the equatorial pressure trough between the two off-equatorial anticyclones. Thus, the Rossby wave-induced frictional convergence favors in part the development of moist Kelvin waves, but the Kelvin-wave induced boundary layer convergence favors its own growth. Therefore, the frictional organization of convective heating couples the Kelvin and Rossby wave but selects eastward propagation for their coupled wave packet.

(iii) Why does the frictional CID mode grow slowly on intraseasonal time scale? Because the frictional convergence is out of phase with the wave-induced moisture convergence (Figure 2), it effectively cuts off the wave-induced heating (the wave-CISK energy source). Thus, the condensational heating rate induced by wave convergence alone is smaller than the adiabatic cooling rate associated with the rising motion, and a catastrophic wave-CISK cannot occur. It is the additional condensational heating associated with the boundary layer frictional moisture convergence and/or the evaporation heat flux that generates instability. That is why the growth rate is an order of magnitude smaller than synoptic scale.

(iv) How does frictional moisture convergence generate the growing CID mode and why does the frictional moisture convergence prefer planetary scales? The generation of eddy available potential energy requires a positive covariance between heating and positive temperature anomalies. The rapid eastward propagation of the dry Kelvin waves warms the dry region east of the precipitation where frictional convergence-induced heating occurs (Figure 2). Thus, the frictional convergence can convert convective energy to perturbation available potential energy. Wang (1988) has shown that the rate of generation of perturbation energy by frictional moisture convergence increases with increasing zonal scale so that the planetary scale unstable mode is preferred.

(v) How does the frictional coupling of Kelvin and Rossby waves slow down the eastward propagation? The coupling-induced off-equatorial rotational cells (Rossby waves) resist eastward propagation because the the beta-effect is constantly trying to pull these rotational cells westward.

When the model is run with a positive-only and SST-dependent heating, it yields a multi-scale CID dispersive wave packet: a global scale circulation coupled with a large-scale (several thousand kilometer) convective complex, which consists of several synoptic scale precipitation cells (Wang and Li 1994). In the boundary layer, strong westerlies flow beneath the major precipitation cells and convergence occurs east of the precipitation complex. Boundary layer friction plays a critical role in forming the multi-cell structure. The planetary circulation scale is due to the spreading of energy by dry Kelvin and Rossby waves that propagate quickly away from the precipitation complex. The energy propagation of the wave packet is slower than that of the individual precipitation cells within the complex and is an additional mechanism for slowing down the eastward propagation of the model MJO disturbance.

4. Mechanism of the boreal summer ISO

The model results indicate that the mean circulation and the distribution of moist static energy (thus SST) play critical roles in determining the seasonal variation of the ISO. As shown in Figure 3, the positive-only heating supports the equatorial eastward propagating Kelvin-Rossby wave packet. However, the reduction of basic-state moist-static energy over Indonesia and the central Pacific weakens the equatorial disturbance and stimulates outflow of moist Rossby waves towards the Indian monsoon and western North Pacific monsoon regions. It is interesting that the emanated moist Rossby cells move west-northwest, forming a northwest-southeast tilted precipitation band (Figure 3) that resembles the observed ISO rain band in the South Asian monsoon region (Ferranti et al. 1997, Annamalai and Slingo 2001, Waliser et al. 2003). Also noteworthy is that the eastward propagation of the tilted precipitation bands gives rise to a northward propagation component in the South Asian monsoon domain.

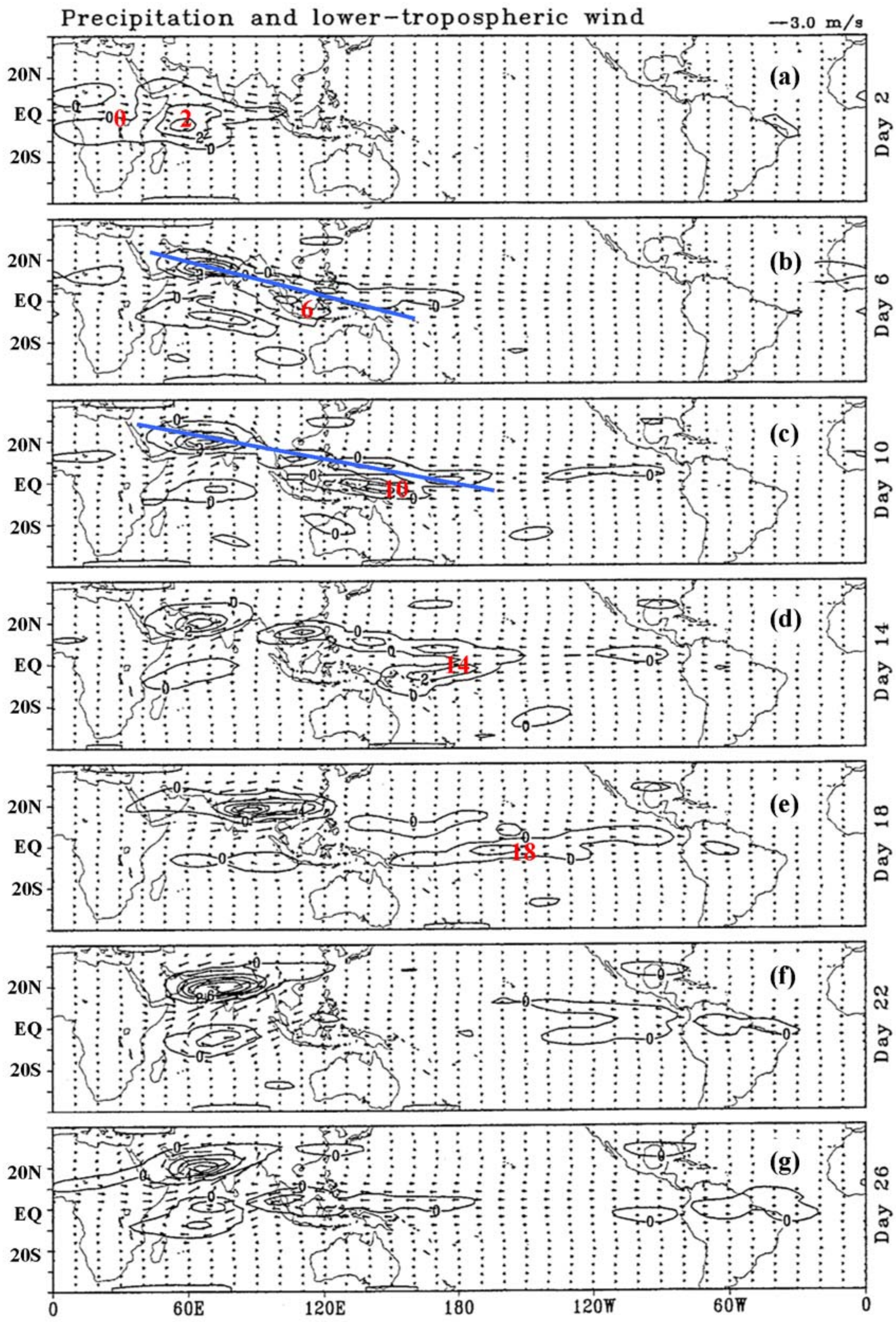

Figure 3 Sequential maps of the lower tropospheric winds and precipitation rate (contour interval is 2 mm/day) in the control experiment of the theoretical model. The solid lines in panel b and c highlight the orientation of the titled precipitation band. The red numbers in each panel indicates the location of the major precipitation center at that day.

What causes the Rossby waves to propagate northwestward and form the NW-SE titled rain band in the Asian summer monsoon region? Obviously, without mean flows, the emanating Rossby waves move westward due to meridional variation in planetary vorticity and in conservation of absolute vorticity. The model simulations show that the monsoon easterly vertical shear provides a mechanism for driving the emanated Rossby waves northward. This mechanism, as illustrated in Figure 4, is essentially the generation of positive vorticity north of the convection through twisting the horizontal vorticity of the basic flow. A mean flow with easterly vertical shear has horizontal relative vorticity with an equatorward component, which the perturbation motion can tap. Rossby-wave-induced heating generates vertical motion perturbation that decreases north of the convection. This vertical motion perturbation field twists the mean flow horizontal vorticity and generates a vorticity with a positive vertical component north of the convection region. The positive vorticity in turn induces convergence in the boundary layer north of the convection, which would destabilize the atmosphere and trigger new convection. For the same reasons, negative vorticity and divergence in the boundary layer develop and suppress convection south of the convection region. Thus, the interaction between Rossby-wave heating and vertical shear of the monsoon creates conditions favor the northward movement of the enhanced rainfall. Another factor that may enhance northward propagation of the disturbances is the intraseasonal fluctuations in SST, which have been shown to lead convection in the northward propagating ISO (Kemball-Cook and Wang 2001, Fu and Wang 2003) The mechanism by which SST strengths convection is essentially the same as that in MJO discussed in the next paragraph.

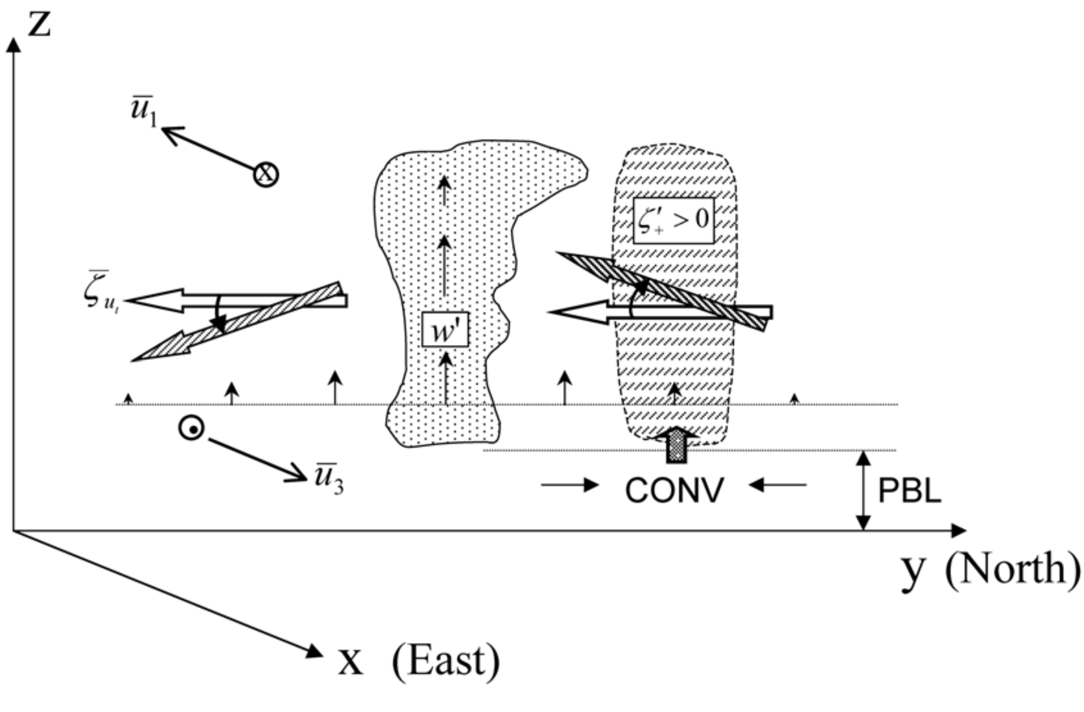

Figure 4 Schematic diagram showing the mechanism by which monsoon easterly vertical shear favors northward propagation of ISO.

5. Role of air-sea interaction

Analyses of the air-sea coupling in the model runs indicate that the basic state of the warm pool is conducive to the occurrence of the coupled unstable CID mode on intraseasonal time scales. The fastest growing coupled CID mode has an east-west planetary scale and stems from the atmospheric moist Kelvin waves. The wind-SST coupling is central to the coupled instability. When wind-SST coupling is relatively weak, the cloud-SST coupling contributes to the growth. This thermodynamic coupling through radiative and latent heat flux at the air-sea interface produces a realistic spatial relationship between SST and convection:

positive SST anomalies occur about 1/6 of the wavelength east of the convection anomalies and about 1/12 of the wavelength west of the surface easterly wind anomaly. The SST-anomaly induced heating tends to enhance the frictional feedback mechanism and increase atmospheric temperature (or thickness) locally so that heating and warming are positively correlated, generating additional eddy available potential energy for the growing coupled mode. The coupling is more effective for planetary perturbations than for shorter spatial scale perturbations. This is because the planetary scale disturbance can have sufficiently long times to change SST; on the other hand, the larger the change in SST, the stronger the feedback from the SST. The coupled model results suggest that while the atmospheric internal dynamics are most important in generating the MJO, the interaction between the atmosphere and the thermodynamic processes of the ocean mixed-layer may play a significant part in sustaining MJO by adding additional instability to moist atmospheric low-frequency perturbations and by providing additional mechanisms for longwave development and slow eastward propagation.

6. Discussion

The major caveat of the current theoretical model is that the cumulus heating process is oversimplified. The total effect of cumulus heating is estimated from the constraint of moisture conservation on convection, and interactive heating is not allowed to be vertically distributed. This confines the description of the heating-induced baroclinic motion to the gravest baroclinic mode. In addition, the model's simplicity does not allow description of the complex cloud-radiation feedback process, which may play an important role in sustaining oscillations on intraseasonal time scales (Hu and Randall 1994, Raymond 2001). Another limitation is that the interaction between the various spatial and temporal scales is neglected. The model presumes a direct interaction between the MJO and convection. However, the MJO is a multi-scale, low-frequency mode of tropical atmospheric motion (Nakazawa 1988). The planetary scale MJO does not directly organize convection, and convective latent heat release is largely consumed directly by mesoscale or synoptic disturbances. In addition, some potentially important processes have not been incorporate into the reduced physics model. For instance, the role of the diurnal cycle on the intraseasonal variability associated with the MJO was emphasized by Slingo et al. (2003), who suggested the diurnal cycle in SST during the suppressed phase of MJO triggers cumulus congestus clouds, which moisten the free troposphere and hence precondition the atmosphere for the next active phase. The present mixed layer model has neglected the effect of the formation of a salinity barrier layer that can potentially provide much stronger local coupling between the atmosphere and ocean on diurnal to intraseasonal time scales (Slingo et al. 2003).

The role of the scale interactions in sustaining the MJO presents a major challenge. Understanding these complex scale interactions and upscale transfer of energy released in convection may shed light on why the AGCMs fail to simulate the MJO. Investigation of the momentum transfer mechanism and advancing a systematic multi-scale model for the MJO (Majda and Klein 2003) are among important steps toward a deeper understanding of MJO dynamics.

Adequate cumulus parameterization is also extremely important for correctly modeling the MJO. The current theoretical model results suggest that if large-scale motion and condensational heating are directly connected through grid scale precipitation, the model has no difficulty in reproducing MJO-like oscillation. In reality, however, one does not know what portion of precipitation in the tropics can be attributed to convective and what to stable precipitation. If all precipitation is convective in the model, then the parameterization scheme has to allow the large-scale low-frequency waves (and associated boundary layer motion) to "feel" the effects of the parameterized convective heating and to have some degree of control on the parameterized convective heating either directly or indirectly (say through correct description of multi-scale interaction processes). If all convective heating were consumed by high-frequency disturbances and if there were no upscale transmit of energy, how would the ISO be maintained?

The current theoretical model results provide clues for the basic mechanisms that may in action in reality. However, to improve representation of the MJO in general circulation models, numerical experiments are necessary with full physical representations that establish the sensitivity of the MJO to the processes and mechanisms and that validate these processes with observations.

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