Mechanism for northward propagation of boreal summer intraseasonal oscillation: Convective momentum transport

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[1] This study demonstrates that the momentum transport by cumulus convection plays a significant role in the organization and northward propagation of intraseasonal (ISO) convection anomalies over the Indian and western Pacific regions during boreal summer. A version of Seoul National University's atmosphere-ocean coupled general circulation model simulates northward propagation when convective momentum transport (CMT) is implemented; the northward propagation disappears when CMT is disabled. An axially symmetric shallow water model with a parameterized CMT is used to understand the role of CMT in the northward propagation of ISO. The basic mechanism of northward propagation is the lower-level convergence to the north of convection, which is induced by the secondary meridional circulation associated with large momentum mixing by convection in the region of large mean vertical shear. A large mean vertical shear exists in South Asian region during boreal summer. **Citation:** Kang, I.-S., D. Kim, and J.-S. Kug (2010), Mechanism for northward propagation of boreal summer intraseasonal oscillation: Convective momentum transport, *Geophys. Res. Lett.*, *37*, L24804, doi:10.1029/2010GL045072.

1. Introduction

[2] Intraseasonal variability is a prominent phenomenon in the tropics, particularly in the Indian and western Pacific Oceans. The most prominent feature of tropical intraseasonal variation is the eastward propagation along the equator with a time scale of about 40 days, which is clearly seen in the boreal winter; this is known as the Madden-Julian oscillation (MJO). On the other hand, the boreal summer intraseasonal oscillation (BSISO) is characterized more distinctively by northward propagation than by eastward propagation in the monsoon region [*Krishnamurti and Subrahmanyam*, 1982; *Chen and Murakami*, 1988; *Goswami*, 1998; *Annamalai et al.*, 1999; *Kemball-Cook and Wang*, 2001; *Lawrence and Webster*, 2002; *Hsu et al.*, 2004]. This northward propagation is closely related to the "active" and "break" periods of the Indian summer monsoon [*Annamalai and Slingo*, 2001] but is rarely seen during the boreal winter.

[3] Several mechanisms have been proposed to explain the northward propagation, which include surface heat fluxes over land [*Webster*, 1983], interaction between convection and moist stability [*Goswami and Shukla*, 1984], air-sea coupled processes [*Kemball-Cook and Wang*, 2001], and emanation of Rossby waves from the eastward propagating convective activity near the equator [*Wang and Xie*, 1997; *Lawrence and Webster*, 2002; *Hsu et al.*, 2004]. Recently, *Jiang et al.* [2004] and *Drbohlav and Wang* [2005] proposed a plausible mechanism in which the BSISO was considered as an unstable mode of the summer mean flow with a large easterly vertical wind shear in the subtropical monsoon region. The key process of the "vertical shear mechanism" proposed by *Jiang et al.* [2004] is the generation of barotropic vorticity due to coupling between atmospheric baroclinic and barotropic modes in the presence of vertical shear in the mean flow. The induced barotropic vorticity further causes a moisture convergence in the planetary boundary layer, which leads to the northward shift of the convection.

[4] Using the Coupled Model Intercomparison Project 3 (CMIP3), *Sperber and Annamalai* [2008] recently demonstrated that the eastward propagation of equatorial convection and easterly vertical wind shear is not only a sufficient condition but a necessary condition for successful simulation of northward propagation in the Indian Ocean region. Meanwhile, *Bellon and Srinivasan* [2006] argued that the scale selection in the vertical shear mechanism proposed by *Jiang et al.* [2004] depends on meridional and Ekman diffusion coefficients that differ from the values suggested by other studies. The above results suggest that both the abovementioned wave-dependent and vertical shear mechanisms cannot fully explain the simulated northward propagation. Although a single mechanism may not be sufficient to completely explain BSISO, all the abovementioned mechanisms may play certain roles in the propagation of BSISO.

[5] In this paper, we propose a new mechanism for the northward propagation of BSISO: the cumulus momentum transport. Convection not only provides heating to the atmosphere but also redistributes the atmospheric momentum vertically by relatively fast convective mixing processes [*Wu and Yanai*, 1994; *Tung and Yanai*, 2002a; *Tung and Yanai*, 2002b]. Convective momentum transport (CMT) has been demonstrated to be important in the momentum budgets for the Walker circulation [*Lin et al.*, 2008] and MJO [*Tung and Yanai*, 2002a, 2002b; *Lin et al.*, 2005]. Recently, climate modeling studies have focused on the role of the CMT in simulations of the seasonal cycle [*Wu et al.*, 2003] and El-Nino Southern Oscillation [*Kim et al.*, 2008; *Neale et al.*, 2008]. *Kug et al.* [2009] also recently showed that the CMT affects the simulation of atmospheric high-frequency activities on time scales of 2–90 days.

[6] The importance of the CMT on the northward movement of the BSISO can be inferred from the multi-model analysis of ISO, documented by *Sperber and Annamalai* [2008]. They showed that the simulated ISOs are mostly

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Table 1. Classification of the Models Used in *Sperber and Annamalai* [2008] With Respect to the Existence of CMT in Them

	With CMT	Without CMT
Northward propagation over India	ECHAM5/MPI-OM, ECHAM4/OPYC, ECHO-G, ECHO-G (MIUB), GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (hires), MIROC3.2 (medres),	CNRM-CM3
No northward propagation		CCSM3.0, CGCM3.1 (T47), CGCM3.1 (T63), CSIRO Mk3.0, FGOALS-g1.0, GISS-AOM, IPSL-CM4, MRI_CGCM2.3.2

weaker than the observed and that half the models fail to simulate the northward propagation. We counted the models with and without the CMT among those used by *Sperber and Annamalai* [2008]. As seen in Table 1, most models with CMT (7 out of 8) simulate the northward propagation, but all of the models without CMT do not show the northward propagation signal. This result implies that the CMT is an important mechanism that should be included in the GCMs to better simulate the observed ISO characteristics.

[7] In the present study, we demonstrate that cumulus momentum mixing by convection in the Indian and western Pacific regions during boreal summer induces a secondary meridional circulation; this results in the northward movement of convection by generating lower-level convergence to the north of the convection. Section 2 demonstrates that the SNU coupled model requires CMT to better simulate BSISO. A simple model framework is given in Section 3 to understand the mechanism for the northward propagation of BSISO. Section 4 presents the subsequent discussions of our findings.

2. CGCM Results With and Without CMT

[8] The ocean-atmosphere coupled GCM of Seoul National University (SNU CGCM) is used in this study. The climatology and ENSO simulations of the CGCM were described by *Kug et al.* [2008]. Two versions of the CGCM are used in this study: one without the CMT (CTL run) and the other with a parameterized CMT (CMT run). These are the same runs as those performed by *Kim et al.* [2008]. The CTL and CMT runs were performed for 200 and 100 years, respectively, and the data for the last 20 years of the runs were used.

[9] Figures 1a–1c show the 20-year means of boreal summer (June–August) precipitation from observations and the CTL and CMT runs, respectively. The model climatologies, which do not greatly differ from each other, are similar to observations in the monsoon continental region but differ from the observations in the tropical Indian Ocean. The northward propagation patterns of intraseasonal variations appearing in the observation and models are shown in Figures 1d–1f. Figures 1d–1f show the lead-lag correlation plots along the 85°–95°E latitude belt, of the 20–100 day filtered pentad-mean precipitation, against ISO index. The ISO index is defined here as the first PC time series of extended EOF for the filtered pentad-mean precipitation data for five temporal lags in the domain of 15°S–30°N and 40°–120°E. In observations (Figure 1d), anomalous convection begins near the equatorial region, slightly south of the equator, and propagates northward with a phase speed

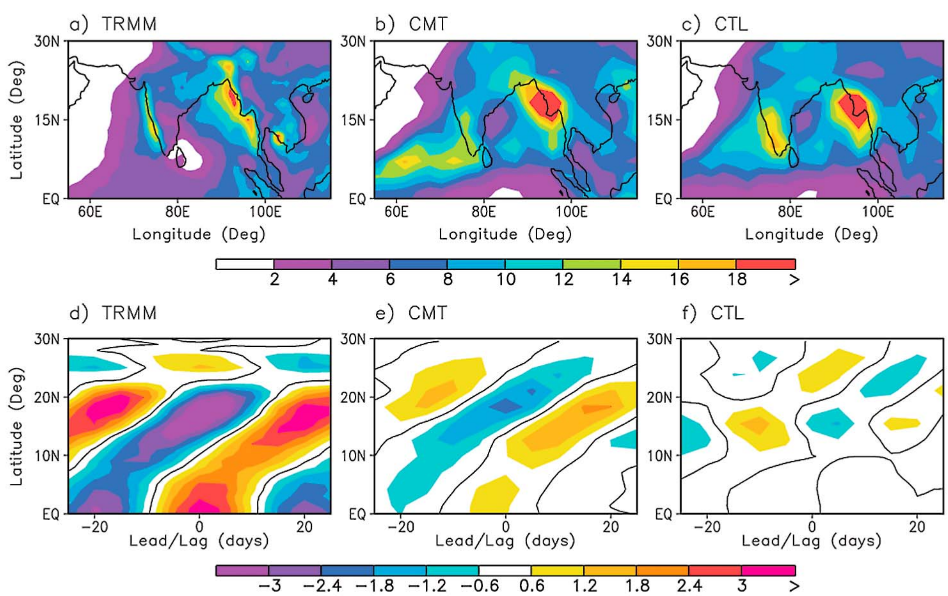

Figure 1. June–September averaged climatological precipitation (mm day^{-1}, shaded) for (a) TRMM, (b) CMT, and (c) CTL. Contour interval is 2 mm day^{-1}. Light and dark shading represent precipitation larger than 6 mm day^{-1} and 12 mm day^{-1}, respectively. Latitude-lag regression plots along the longitude average of 85°–95°E for the precipitation anomalies (mm day^{-1}) with time scales of 20–100 days for (d) TRMM, (e) CMT, and (f) CTL. In latitude-lag regression plots, contour interval is 0.6 mm day^{-1} and dashed lines represent negative values.

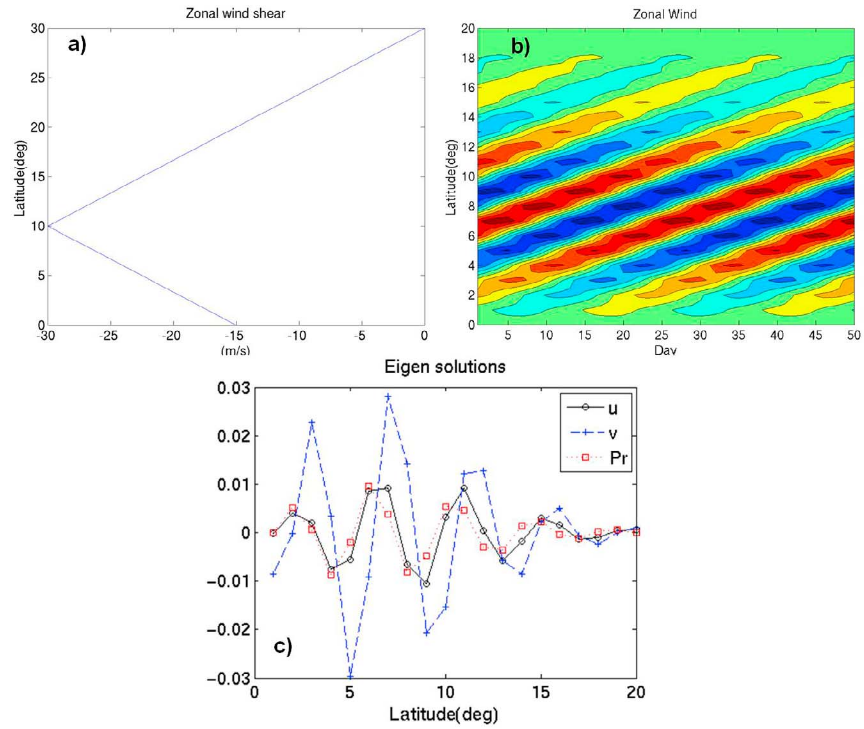

Figure 2. (a) Zonal wind shear used in the present model. (b) Eigen solution of the zonal wind for the most unstable mode. Negative values are represented with dashed lines. (c) The first eigen mode (unstable mode) of zonal wind (solid), meridional wind (dashed), and diagnosed precipitation (dotted box) as a function of latitude.

of about 0.7° day^{-1}. The model without the CMT (CTL run) poorly simulates the northward propagation (Figure 1e). However, the simulation quality significantly improved with the inclusion of the CMT (Figure 1f). The modeled northward propagation began near 10°N because of the lack of precipitation in the equatorial Indian Ocean, indicating that equatorial convection is not a necessary condition for initiation of the northward propagation.

3. A Simple Model Framework

[10] In the tropics, large-scale circulation can be described reasonably well by the first baroclinic mode, which can be simplified as a shallow water system [*Matsuno*, 1966]. In the shallow water system, the CMT can be parameterized in terms of mean vertical shear *U* and precipitation, and the precipitation can be expressed with the lower-level convergence, as in the work of *Kang and Held* [1986]. After taking the zonal mean—since we are interested in only meridional propagation—and after considering the above parameterization of CMT, the non-dimensionalized equations for a shallow water system in a beta-plane are expressed as

$$\frac{\partial u}{\partial t} - yv = AU\frac{\partial v}{\partial y}, \tag{1}$$

$$\frac{\partial v}{\partial t} + yu = -\frac{\partial \Phi}{\partial y}, \tag{2}$$

$$\frac{\partial \Phi}{\partial t} + m\frac{\partial v}{\partial y} = 0. \tag{3}$$

Here, the units of time and length are expressed as [T] = $(c\beta)^{-1/2}$ and [L] = $(c/\beta)^{-1/2}$, β (= 2.29 × 10^{-11} m^{-1} s^{-1}) is the meridional gradient of the Coriolis parameter at the equator, and c (= $(gH)^{1/2}$, 50 m s^{-1}) is the velocity of pure gravity waves. A (= 0.003) is the CMT efficiency for unit divergence, which is in a reasonable range of the parameter value, as inferred from the GCMs with CMT. In the above system, *m* (= −0.05) can be regarded as a moist static stability parameter, and the value represents a slightly unstable condition of large-scale convective system over the Asian monsoon region during boreal summer. The mean zonal wind shear *U* specified in the model is shown in Figure 2a, which can represent the summer-mean vertical shear over the Indian Ocean and south Asia.

[11] The eigensolution for the most unstable mode obtained with equations (1)–(3) is shown in Figure 2b. Figure 2b clearly shows the northward propagation, although the details of the propagation characteristics are slightly different from the observations. The propagation speed is slightly faster, and the meridional scale of the convection was shorter than the observed. However, this result is encouraging when we consider several mechanisms missing in this simple model, such as nonlinear processes and more complicated heating and cooling processes, which may be responsible for better simulation of the phenomenon. The system showed no propagation when *A* = 0, indicating that the CMT is crucial for the northward propagation. It is also mentioned that the northward propagation characteristics depends on the parameters of m and A in the model. The system slows down when m has a relatively large negative value (more unstable condition). However, when the system is stable, the time

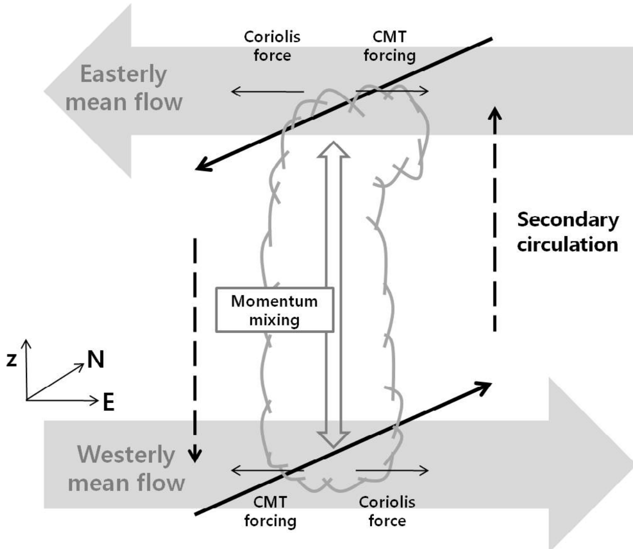

Figure 3. Schematic diagram of the three-dimensional circulation and convection in the presence of the CMT mechanism under the mean condition of a large vertical shear in the zonal wind, represented by the large grey arrows.

scale becomes about 10 days, which is much shorter than the unstable case. *Lau and Li* [1984] documented the northward propagation mode with a time scale of about 2 weeks in Eastern China during boreal summer. Such a variety of time scales may be related to the convective conditions of the basic state. The propagation speed also affected by the value of A, the efficiency parameter of CMT. The propagation becomes faster when A has a larger value. Further study is required for investigating the dependency of northward propagation characteristics on the parameters mentioned above.

[12] Figure 2c shows the phase relationships among the zonal and meridional wind components of the most unstable mode as well as the predicted precipitation. Note that the zonal wind anomaly was in phase with precipitation anomaly because the zonal momentum was changed by the CMT, but the meridional wind anomaly was in a quadrature relationship with the precipitation. In the northward propagation context, the positive (negative) convection leads the negative (positive) meridional wind component. In the present first baroclinic model, the negative meridional wind implies the upper-level southerly and lower-level northerly wind; therefore, the convection leads the northerly wind and lower-level convergence to the north of the convection. This lead-lag relationship of meridional wind and convection resulted in the northward propagation of the convection.

[13] The key dynamics associated with the northward propagation can be illustrated more clearly with the simplified two-layer baroclinic system shown in Figure 3. In the mean state with a large easterly vertical shear (noted by thick shaded arrows in Figure 3), the convection provides easterly momentum in the lower layer and westerly momentum in the upper layer. Such zonal wind tendencies by the CMT should be balanced by a secondary meridional circulation with the Coriolis force. As a result, as seen in Figure 3, the anomalous southerly and northerly winds are induced in the lower and upper layers, respectively. The anomalous meridional winds induce the lower-layer convergence and upper-level divergence to the north of the convection, resulting in the northward propagation of the convective system.

4. Discussion

[14] It may be interesting to discuss the present mechanism with the similar mechanism proposed by *Jiang et al.* [2004]: the essential dynamics of their mechanism is also associated with a large mean vertical shear. The difference between the two mechanisms is discussed here in terms of the zonal momentum and two-layer vorticity equations. The zonal momentum equation with a mean vertical shear can be expressed as

$$\frac{\partial u}{\partial t} + \omega\left(\frac{\partial \bar{u}}{\partial p}\right) - fv = F, \tag{4}$$

where p is the pressure; ω, the pressure velocity; $\bar{u}$, the mean zonal wind; and f, is the Coriolis parameter. Note that *Jiang et al.* [2004] used an f-plane model. The equation has a vertical advection term and the cumulus friction term F. The vertical advection term vanishes in the first baroclinic equation in a two-layer model to result in equation (1). However, the barotropic equation retains the vertical advection term, which is a crucial term for the northward propagation according to *Jiang et al.* [2004]. They discussed the northward propagation in terms of the barotropic vorticity equation (equation (A15) of their paper), which can be simplified by the equation

$$\frac{\partial \zeta_+}{\partial t} = \bar{u}_T \frac{\partial \delta_-}{\partial y}, \tag{5}$$

where ζ is the vorticity, δ is the divergence, $\bar{u}_T$ is the mean wind shear, and the subscripts + and − represent the barotropic and baroclinic components, respectively. We assumed in equation (5) that the vertical mean divergence δ_+ is close to zero and that no friction works other than CMT. CMT does not contribute to the barotropic vorticity tendency because it redistributes the momentum vertically; the net momentum change by CMT is zero. The essential dynamics according to *Jiang et al.* [2004] is the generation of barotropic vorticity to the north of the convective (lower-level convergence) region and the interaction of the PBL with the barotropic vorticity; this induces convergence near the surface and moisture convergence, resulting in the northward propagation of the convective system.

[15] In contrast, the barotropic component of vorticity is zero in the present study, and the baroclinic vorticity equation can be written as

$$\frac{\partial \zeta_-}{\partial t} + f\delta_- = -A\bar{u}_T \frac{\partial \delta_-}{\partial y}, \tag{6}$$

where the term on the right hand side is due to CMT. As mentioned above, the vertical mean advection term does not contribute to the generation of baroclinic vorticity, and CMT is the only mechanism in the present simple system, which directly changes the circulation associated with the first baroclinic mode. The circulation (baroclinic vorticity) tendency is in a quadrature relationship with CMT due to the convection associated with baroclinic divergence, resulting in meridional movement of the circulation system. As mentioned above, *Jiang et al.*'s [2004] theory requires a barotropic component for vorticity and PBL frictional convergence, while the present study considers only the baroclinic component of vorticity, and the CMT can induce northward propagation of the baroclinic components directly in a free atmosphere without the PBL.

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