Effects of air–sea coupling on the eastward propagating boreal winter intraseasonal oscillation over the tropical Indian Ocean

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\textbf{ABSTRACT}

The effects of air–sea coupling over the tropical Indian Ocean (TIO) on the eastward propagating boreal winter intraseasonal oscillation (MJO) are investigated by comparing a fully coupled and a partially decoupled Indian Ocean experiment using the SINTEX-F coupled model. Air–sea coupling over the TIO significantly enhances the intensity of the eastward propagations of the MJO along the 5°–10°S zonal areas. The zonal asymmetry of the SST anomaly (SSTA) is responsible for the enhanced eastward propagation. A positive SSTA appears to the east of the MJO convection, which results in the boundary layer moisture convergence and positively feeds back to the MJO convection. In addition, the air–sea interaction effect on the eastward propagation of the MJO is related to the interannual variations of the TIO. Air–sea coupling enhances (reduces) the eastward-propagating spectrum during the negative Indian Ocean dipole mode and positive Indian Ocean basin mode. Such phase dependence is attributed to the role of the background mean westerly in affecting the wind–evaporation–SST feedback. Air–sea coupling (decoupling) enhances (reduces) the zonal asymmetry of the low-level specific humidity, and thus the eastward propagation spectrum of the MJO.

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\textbf{1. Introduction}

Intraseasonal oscillation (30–60-day oscillation) was first detected by Madden and Julian (1971, 1972). The MJO is important because of its considerable influence on monsoon dynamics, general weather, and climate variability, and as an important part of the ENSO cycle (Li and Zhou 1994; Li and Liao 1998; Jones 2000; Sobel and Maloney 2000; Hall, Matthews, and Karoly 2001; Bond and Vecchi 2003; Barlow et al. 2005; Jeong et al. 2008; Wheeler et al. 2009). Recent observational and modeling studies have shown that ocean–atmosphere coupling is crucial for the maintenance of the MJO. Observations obtained from TOGA COARE indicate that short-term (weekly to monthly) fluctuations of SST in the western Pacific warm pool are closely linked to the alternation of wet and dry spells driven by the MJO, which is modulated by a combination of anomalous latent heat flux and insolation (Weller and Anderson 1996; Hendon and Glick 1997; Lau and Sui 1997). Variations of shortwave radiation and latent heat flux are equally important for driving the SST variations in the western Pacific, while latent heat flux variations are less important in the Indian Ocean (Flatau et al. 1997). The diurnal cycle of shortwave radiation is found to significantly increase the intraseasonal amplitude of SST over that produced by daily mean insolation (Shinoda and Hendon 1998). Bernie et al. (2005) and Li et al. (2013) also

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addressed the impact of the diurnal cycle on intraseasonal SST amplitude.

Furthermore, incorporating ocean–atmosphere coupling into a model improves the simulation of the MJO in terms of its activity, propagation characteristics, seasonality, and predictability (Walisser, Lau, and Kim 1999; Woolnough, Slingo, and Hoskins 2000; Li and Yu 2001; Fu and Wang 2004; Zheng et al. 2004; Fu et al. 2007; Woolnough, Vitart, and Balmaseda 2007; Kim et al. 2008; Pegion and Kirtman 2008; Kim et al. 2010; Klingaman et al. 2011). Tan, Zhang, and He (2003) revealed two dominant SST modes in the tropical Indian Ocean (TIO), one being a basin-wide pattern (hereafter IOB) and the other a zonal dipole pattern (hereafter IOD). TheIOD has a significant impact on the intensity of boreal summer northward-propagating intraseasonal oscillation (BSISO) (Ajayamohan, Rao, and Yamagata 2008; Ajayamohan et al. 2009; Lin et al. 2011). However, to what extent the interannual SST variations over the TIO regulate the effect of intraseasonal air–sea coupling on the MJO is not known from previous studies. In this study, we investigate this by comparing 70-year integrations of a coupled and decoupled atmosphere and ocean model.

2. Model and data

The relatively high-resolution CGCM used in this study is SINTEX-F (Luo et al. 2003, 2005). This model was developed at the FRCGC and was based on the original European SINTEX model (Gualdi et al. 2003; Guilyardi et al. 2003). TheOcean component uses an Arakawa-C-type grid based on a 2° Mercator mesh. The atmospheric component is ECHAM4.6, in which a high horizontal resolution (T106) of approximately 1.1° × 1.1° is used. More detailed information on the model can be found in Luo et al. (2005).

In our study, two experiments are designed. In the control experiment (CTL), the atmosphere and ocean are coupled globally. In the sensitivity experiment (pdIO), the atmosphere and ocean are not coupled in the TIO (30°S–30°N), but are coupled elsewhere. In the pdIO experiment, the atmospheric model is forced by monthly-mean SST over the TIO derived from the CTL run. It should be noted that the prescribed SST in the TIO in the pdIO experiment is not the climatological SST, but has the same interannual variations as in the CTL run. Both experiments are integrated for 70 years starting from the same initial conditions. The outputs consist of 20 variables; for example, 3D temperature, wind fields, specific humidity from 200 to 850 hPa, and surface OLR (Liebmann and Smith 1996). Excluding the first 20 years used as the spin-up run, we analyze only the last 50 years of model outputs. To estimate the reliability of the model simulation, daily averaged OLR data from NCEP with a 2.5° × 2.5° resolution are used and processed into a pentad mean for comparison with the model output.

A finite-domain (25°S–25°N, 40°–180°E) wavenumber-frequency analysis is applied to transform the OLR field from a spatiotemporal domain to a wavenumber-frequency domain (Hayashi 1982; Chen, Wang, and Zeng 2000; Lin and Li 2008). ‘Winter’ in this paper refers to the period from November to April. A Lanczos band-pass filtering (Trenberth 1984) is used to isolate the 10–90-day components from original data, which takes the annual mean and the first four harmonics.

3. Effects of air–sea coupling on the MJO spectra

The eastward-propagating MJO spectra in CTL is stronger than that in pdIO (Figure 1). The most remarkable difference is found around the areas of 5°–10°S in pentads 6–10 (Figure 1(c)). The difference in the eastward-propagating MJO spectrum averaged over the latitudinal bands of 5°–10°S in pentads 6–20 between CTL and pdIO exceeds 25% of the climatological values. This means that intraseasonal air–sea coupling over the TIO plays a key role in significantly strengthening the MJO’s intensity.

In this paper, 482 strong eastward propagation events are selected both in CTL and pdIO every 10° of longitude from 50°E to 140°E. Figure 2(a) and (b) illustrate that a positive SST anomaly is always located in the east of the convection center and leads the convection moving eastward, which means that MJO convection and SST are strongly coupled and move eastward sequentially. For a fixed observer at a reference longitude, the SST leads the MJO convection by about two pentads, indicating positive feedback from the SST to the convection. Without the SST positive feedback, weaker eastward-propagating MJO convection is apparent in pdIO (Figure 2(c) and (d)). The role of intraseasonal SST in enhancing the eastward-propagating MJO convection can be seen more clearly in Figure 2(e) and (f). Figure 3(a) and (b) show that both the humidity and divergence field exhibit a clear zonal asymmetry in CTL and a weak zonal asymmetry in pdIO, with the maxima in humidity and 850-hPa convergence located to the east of the convection center. This zonal asymmetry is partially responsible for the eastward propagation of the MJO over the Indian Ocean. The cause of the wind and divergence differences is arguably attributable to the effect on the zonal SST asymmetry in the presence of air–sea coupling. The background low-level zonal wind is westerly along 5°–10°S areas during boreal winter, based on observational data. In response to the MJO convective heating, an easterly (westerly) anomaly appears to the east (west) of the convection center. This leads to a decrease (increase) in total wind speed (solid line in Figure 3(c)), and thus reduced (increased)
surface evaporation in the east (west) of the convection center. The asymmetry of surface evaporation, along with enhanced (reduced) downward solar radiation in the east (west) of the convection center, leads to the asymmetric SSTA distribution: a positive (negative) SSTA in the east (west) of the convection center (solid line in Figure 3(d)). The mechanism proposed by Lindzen and Nigam (1987) is put forward to explain the results that anomalous boundary-layer convergence can be generated over the positive SSTA, which leads to a further increase in local moisture. Decoupling cases in the Indian Ocean (pdIO) also have similar asymmetries of divergence, humidity, wind speed, and surface evaporation fields (dashed lines in Figure 3) as in CTL, but with weaker amplitude. The weaker asymmetric amplitudes lead to a weaker eastward-propagating MJO spectrum in pdIO than that in CTL.

4. Dependence of air–sea coupling effects on Indian Ocean dipole and basin modes

For further examination, the TIO interannual SST variations are divided into four types: a positive IOD year, a negative IOD year, a positive IOB year, and a negative IOB year. The IOD index is defined according to that of Saji et al. (1999). The IOB index is defined as the sum of SSTAs in the western and eastern Indian Ocean, using the same boxes as for the IOD. An index is introduced to measure the intensity of the eastward-propagating mode over the

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**Figure 1.** The composite OLR spectrum (units: W$^{-2}$ m$^{-4}$) of the zonal wavenumber-1 eastward-propagating MJO in (a) CTL, (b) pdIO, and (c) their difference (CTL − pdIO) during the 49-year period. Shading in (c) denotes that the differences exceed the 95% confidence level.
The zonal gradient of the SST is different (Figure 5, gray bars). During the positive IOD and negative IOB years, the zonal gradient of the SST is negative and results in an anomalous easterly. The anomalous easterly reduces the background westerly, leading to a weaker eastward-propagating MJO. In contrast, during the negative IOD and positive IOB years, the zonal gradient of the SST is positive and enhances the background westerly, leading to a stronger eastward-propagating MJO. This result is different from the summer condition that Lin, Li, and Li (2010) found, in which the negative (positive) gradient of SST corresponds to easterly (westerly) flow in all SST interannual modes in the TIO. Because the interannual variability of SST in the TIO grows during summer (5–10 month May–October) and peaks in fall, 5°–10°S areas (hereafter IEP). The IEP is defined as the wavenumber-1 OLR spectrum averaged over 5°–10°S with a period of 6–20 pentads, based on Figure 1(a) and (c). The differences are positive during negative IOD years and positive IOB years, but negative during positive IOD and negative IOB years (figure omitted). This indicates that air–sea coupling enhances (reduces) the eastward-propagating spectrum during the negative IOD mode and positive IOB mode.

Under a normal westerly condition, in response to the east of the MJO convection, a Kelvin wave reduces the surface wind speed and warms the sea surface. The resultant positive SSTA to the east of the convection generates the boundary-layer convergence and humidity increase, leading to the eastward propagation of the MJO convection (Li et al. 2003). However, such a coupling effect would be reversed when the background westerly alters to easterly. The change in the background zonal wind is closely related to the zonal gradient of the SST. In winter, mean zonal winds over 5°–10°S are the same (westerly) in all SST interannual variation modes (Figure 4, solid line). However, the zonal gradient of the SST is different (Figure 5, gray bars). During the positive IOD and negative IOB years, the zonal gradient of the SST is negative and results in an anomalous easterly. The anomalous easterly reduces the background westerly, leading to a weaker eastward-propagating MJO. In contrast, during the negative IOD and positive IOB years, the zonal gradient of the SST is positive and enhances the background westerly, leading to a stronger eastward-propagating MJO.
the interannual variability of SST in the TIO is small. The anomalous zonal gradient of SST cannot lead to the reversal of surface wind.

the anomalous zonal gradient of SST can result in large anomalous wind disturbance. The anomalous easterly wind response to the negative zonal gradient is strong enough to change the surface westerly wind to easterly and reduce the eastward-propagating BSISO. In contrast,

Figure 3. Structures of the eastward-propagating MJO along 5°–10°S with respect to the convection center at every 10° of longitude from 50°E to 140°E, in CTL (solid lines) and pdIO (dashed lines): (a) 850-hPa divergence (units: 10^{-6} \text{s}^{-1}); (b) 850-hPa specific humidity (units: 10^{-4} \text{kg kg}^{-1}); (c) surface zonal wind at 10 m (units: m s^{-1}); (d) SST (units: 10^{-1} K). The abscissa is the relative longitude, with 0 being the MJO convection center.

Figure 4. The IEP power spectrum differences between CTL and pdIO for different interannual SSTA modes over the TIO. Horizontal axis means different interannual SSTA mode: Dip+, positive IOD mode; Dip−, negative IOD mode; Bas+, positive IOB mode; Bas−, negative IOB mode.

Figure 5. The background 10-m zonal wind (units: m s^{-1}) averaged over (50°–140°E, 5°–10°S) and zonal SST gradient along 5°–10°S (difference between 90°–110°E and 50°–70°E; units: K), composed based on different interannual SSTA modes. The left axis is the zonal SST gradient and the right axis is 10-m zonal wind.

the interannual variability of SST in the TIO is small. The anomalous zonal gradient of SST cannot lead to the reversal of surface wind.
5. Summary

The effects of air–sea coupling over the TIO on the MJO's eastward propagation, and the modulation effect of air–sea coupling by Indian Ocean SST interannual variation, were examined by comparing a fully coupled (CTL) and partially decoupled Indian Ocean (pdIO) experiment using the SINTEX-F CGCM. It was found that air–sea coupling over the TIO significantly enhances the eastward propagation along 5°–10°S. When air and sea are coupled over the TIO, MJO convection and SST are well coupled and move eastward sequentially: a positive SSTA is always located in the east of the convection center and leads the convection moving eastward. It enhances the eastward-propagating intensity through a zonally asymmetric SST response. In boreal winter, the low-level background zonal wind along 5°–10°S is westerly. The anomalous easterly to the east of the MJO convection decreases the wind speed and thus the evaporation, leading to a positive SSTA. The positive SSTA in turn forces a boundary-layer convergence, which further increases the boundary-layer humidity and atmospheric instability, enhancing the eastward propagation of the MJO convection.

Further analysis reveals that the air–sea coupling effects can be modulated by the interannual SST variations over the TIO. The impact of air–sea coupling on the eastward propagation of the MJO is enhanced during negative IOD and positive IOB years, but weakened during positive IOD and negative IOB years. The cause of this phase dependence is attributed to the change in the background zonal wind over the Indian Ocean. The change in the background zonal wind is closely related to the zonal gradient of the SST. During positive IOD and negative IOB years, the zonal gradient of the SST is negative and results in an anomalous easterly, leading to a weak eastward-propagating MJO. In contrast, during negative IOD and positive IOB years, the zonal gradient of the SST is positive and enhances the background westerly, leading to a stronger eastward-propagating MJO. Therefore, the simulation results demonstrate that the impact of air–sea coupling on the eastward-propagating MJO is substantially modulated by the interannual variation of the TIO.

Disclosure statement

No potential conflict of interest was reported by the authors.

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