Sensitivity Experiments on the Role of Water Vapor in the Eastward Propagation of MJO

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Abstract

In this study, we employed the nudging assimilation of the Weather Research and Forecasting (WRF) model to conduct a set of sensitivity experiments on the role of water vapor in the Madden-Julian Oscillation (MJO) eastward propagation, focusing on the eastward propagating 30-60d low-frequency component in the tropical atmosphere from the Indian Ocean to the western Pacific Ocean during September-November 2004. Using 11 different cumulus parameterization schemes, the simulation results show that the ability of the regional climate model in simulating the MJO eastward propagation is sensitive to the cumulus scheme: A suitable scheme can well reproduce the MJO eastward propagation characteristics, while most schemes show no skill for the MJO eastward propagation. When the water vapor in the model domain was assimilated using reanalysis data with nudging technique, we found that the low-frequency evolution of the tropical zonal wind exhibits MJO features well, and the low-frequency phase of water vapor is ahead of the zonal wind by about 6-7 days, which suggests that the atmospheric water-vapor distribution is the key factor for the eastward propagation of the MJO, and the effect of water-vapor field via affecting the atmospheric stability. When the atmospheric temperature assimilation was conducted, there was almost no improvement in the skill of MJO simulation.

1. Introduction

The Madden-Julian Oscillation (MJO) is the dominant intra-seasonal oscillation mode in the tropics (Madden and Julian 1972), which has a planetary-scale spatial structure dominated by zonal wave-numbers 1–3, eastward propagation, exhibiting a broad-band oscillation cycle of 30-60d (Li et al. 2007). A lot of previous studies have shown that similar low-frequency oscillations are found everywhere in the world, and they can propagate in different directions (Li and Li 1997; Chen et al. 2001; Li 2014). The activity and anomalies of the MJO affect regional weather and climate. For example, the convergence of the southward propagating MJO in the mid and high latitudes of East Asia and the northward propagating MJO in the Yangtze and Huai river basins of China will produce persistent precipitation in the Yangtze River basin and North China in summer; and these regions are more prone to flooding in years of strong MJO activity (Yang and Li 2003). In addition, the intensity of precipitation in East China varies with the propagation of the MJO. When the tropical MJO travels eastward to the Indian Ocean, precipitation in East China increases; whereas the MJO travels to the western Pacific, precipitation in East China decreases. Meanwhile, there are seasonal differences in MJO’s effects on precipitation (Jia et al. 2011). Therefore, it is important to study the propagation mechanism of the MJO for better precipitation prediction in East China.

Simulation studies on intra-seasonal oscillations in the tropical atmosphere have shown that numerical models have difficulty in capturing the characteristics of MJO activities; and none of the models participating in the Atmospheric Model Intercomparison Project (AMIP) can accurately characterize the main features of the MJO (Slingo et al. 1996). At present, most models produce short intra-seasonal oscillation periods and weak oscillation intensity, and are unable to describe the seasonal differences of the MJO, and even its continuous eastward propagation characteristics (Kim et al. 2009).
Various theories have been proposed to explain the MJO eastward propagation. The theoretical model proposed by Emanuel (1987) and Neelin (1987) emphasizes the effect of east-west asymmetry of surface heat flux on the generation and eastward propagation of the MJO. However, this theory assumes that surface mean winds are easterly winds of a certain strength, but observations show that surface easterly winds are prevalent only over the central-eastern Pacific and Atlantic Ocean; thus, it cannot explain the generation and propagation of the MJO throughout the tropics (Wang 1988). Based on a series of assumptions, Wang (1988) considered the MJO as a convection-coupled Kelvin wave, and numerical experimental simulations yielded mostly unstable modes with short wavelengths and too fast eastward propagation. Wang and Li (1994) considered the MJO as a Kelvin-Rossby wave coupled with convection and boundary-layer friction effects (Wang and Li 1994). More recent theories emphasized the role of sea-air interactions (Wang and Xie 1998) and water-vapor distribution (Maloney 2009; Hsu and Li 2011; Sobel and Maloney 2013).

Regional climate models (RCMs) are an effective tool for obtaining high-resolution regional information on weather-climate evolution (Xu et al. 2019). The nudging method used in the process of dynamic downscaling numerical simulations using RCMs is a way to maintain small- and medium-scale dynamic characteristics in RCMs while preserving large-scale features, so that the model simulation results approximate the real conditions (Wang and Kotamarthi 2013). Sperber (2003) found that in the specific humidity and vertical velocity fields of the MJO, specific humidity profile and vertical motion profile are similar, both tilting westward with height, that is, there is a zonal asymmetry with respect to the tilt axis. Maloney (2009) showed that before the occurrence of lower-level easterly wind anomalies, the column-integrated moist static energy (MSE) accumulates prior to precipitation, and with the occurrence of westerly wind anomalies, MSE discharges during and after precipitation. The MSE anomalies occurred in the lower troposphere are mainly regulated by specific humidity anomaly. Hsu and Li (2012) demonstrated that the distinct zonal asymmetric distribution of the water-vapor field in the boundary layer with respect to the convective center is the key to the maintenance of the MJO eastward propagation. In the model simulation, however, different cumulus parameterization schemes have different effects on the simulation of the water vapor field. It is shown that the model's lack of ability to simulate the MJO is largely influenced by the model's cumulus parametrization scheme (Duvel et al. 2013). In this paper, we use different cumulus parameterization schemes to numerically simulate an individual case of MJO eastward propagation to verify the sensitivity of the Weather Research and Forecasting (WRF) model to cumulus parameterization schemes in simulating the effect of MJO eastward propagation, and then use the nudging assimilation of the WRF model to investigate the effects of different spatial distributions of atmospheric variable fields on the simulated MJO eastward propagation process.

The article is organized as follows. In Sect. 2, we present the model, datasets and method used. In Sect. 3, we analyze the simulation results of different cumulus parameterization schemes. In Sect. 4, we describe the nudging simulation and analyze the simulation results. Conclusions are presented in Sect. 5.
2. Model, Datasets And Method

2.1 Model

The WRF model is a fully compressible non-hydrostatic model with a vertical coordinate system that follows the hydrostatic coordinate system of the terrain, and uses an interleaved grid of the Arakawa C grid, which is beneficial for improving accuracy in high-resolution simulations. In this study, WRF V4.0 model is used.

2.2 Datasets

The data used in this paper include daily reanalysis products from the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR), with a resolution of 2.5° × 2.5° (referred to as Re1) for the period from 1 January 1985 to 31 December 2019. Re1 has 17 layers in the vertical direction. The variables include horizontal velocity, vertical velocity, geopotential height, air temperature, and specific humidity. The data can be downloaded at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html.

The numerical simulation of individual MJO eastward propagation case is forced by the NCEP four-time daily reanalysis data with a horizontal resolution of 1° × 1° (referred to as Re2) for the time period from 0000 UTC 1 September 2003 to 0000 UTC 1 May 2005. Re2 can be downloaded from https://rda.ucar.edu/ datasets/ds083.2/.

2.3 Method

2.3.1 Bandpass filtering

Bandpass filtering is often used for extracting low-frequency signals. It was pointed out that for longer time series, the Lanczos filter has the distinct advantage of effectively suppressing spurious Gibbs waves due to finite truncation and having narrow transition bands (Duchon 1979). Therefore, we used a 100-point Lanczos filter to extract the 30-60d component of atmospheric variables.

2.3.2 Correlation coefficient

The correlation coefficient between two fields is calculated as follows,

\[ r(X, Y) = \frac{\text{Cov}(X,Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}} \]  \hspace{1cm} (1)

where \( X \) and \( Y \) are two different fields, \( \text{Cov}(X,Y) \) is the covariance of \( X \) and \( Y \), and \( \text{Var}(X) \) and \( \text{Var}(Y) \) are the variances of \( X \) and \( Y \), respectively.

2.3.3 Case selection and nudging simulation
The MJO has a planetary-scale spatial structure dominated by zonal wave numbers 1-3 and eastward propagation. To study the eastward propagation characteristics of the MJO, we select a typical 30-60d propagation process in the tropics (10°S-10°N) from the Indian Ocean to the western Pacific Ocean (30°-130°E) in the autumn (September-November) of 2004 as the study object based on 30-60d filtered time-longitude maps of tropical (10°S-10°N) mean zonal winds at 200 and 850 hPa from 1985 to 2019 of the Re1 data (not shown). Figure 1 shows the time-longitude maps of the tropical mean zonal winds at 200 and 850 hPa from the Indian Ocean to the western Pacific Ocean in September-November 2004. We can see that the 30-60d low-frequency components of the zonal winds at both 200 hPa (Fig. 1a) and 850 hPa (Fig. 1b) have obvious eastward propagation characteristics, and the amplitude of zonal winds at 200 hPa is stronger than that at 850 hPa, but the continuous eastward propagation characteristics of the zonal winds at 850 hPa are more obvious. So, the results of the 30-60d low-frequency component of the zonal winds at 850 hPa will be our focus in the subsequent analysis.

Nudging assimilation is an option in the WRF model to assimilate the simulated variables to the large-scale driving field during the simulation, and different variables can be selected. When using the reanalysis data as the driving force for WRF model simulation, the variables selected to be nudged in the model domain will be assimilated toward the reanalysis data, ensuring that there will be no large deviation between the simulated value of the variable and the reanalysis (Stauffer and Seaman 1994; Liu et al. 2008).

To test the simulation effect of the numerical model on the eastward propagation characteristics of MJO in the Indo-western tropical Pacific in the autumn of 2004, we selected the simulation area shown in Fig. 2. The model adopts the Mercator projection with the center located at 80°E on the equator. The horizontal resolution is 50 km, and the number of horizontal grid points is 314 × 140. There are 45 layers, and the pressure at the top of the model layer is 10 hPa. The Re2 reanalysis data are used for the initial field and lateral boundary conditions, and the sea-surface temperature (SST) is updated every six hours. The simulation is initialized at 0000 UTC 1 September 2003 and ends at 0000 UTC 1 May 2005, a total of 608 days. The time step is 300 seconds, and the model outputs are stored daily.

The physical parameterizations used in this study include the WSM6 microphysics scheme (Hong and Lim 2006), the Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997) for longwave radiation calculation, the Dudhia scheme (Dudhia 1989) for shortwave radiation calculation, the Eta similarity scheme (Monin and Obukhov 1954; Janjić 1994, 1996, 2002), the five-layer thermal diffusion scheme (Dudhia 1996) for land surface processes, and the Mellor-Yamada-Janjić boundary layer scheme (Mesinger 1993; Janjić 1994). Eleven cumulus parameterization schemes are selected for the simulations (Tab. 1). More details of the physical parameterizations are described in the WRF user’s guide (Skamarock 2019).

Figure 1 shows the time-longitude maps of the 30-60d components of the mean zonal winds at 200 and 850 hPa simulated using the 11 cumulus parameterization schemes, which are plotted separately, and the best and worst cumulus parameterization schemes for simulating the 30-60d components in autumn.
2004 are determined by calculating the correlation coefficients of the 30-60d component amplitude distributions on these maps from simulations and observations. According to Hsu and Li (2012), the asymmetric water-vapor distribution between the east and west sides of the maximum amplitude of the MJO is a necessary condition for its eastward propagation. The water vapor is assimilated in the worst cumulus parameterization scheme for simulating the eastward propagation of the MJO, that is, the simulated water-vapor mixing ratio is nudged to the observed value (reanalysis field, hereafter) during the simulation, and the improvement of the model for the eastward propagation of the MJO is examined.

3. Comparative Analysis Of Simulation Results Of Different Cumulus Parameterization Schemes

Figures 3 and 4 show the time-longitude maps of the 30-60d components of the mean zonal winds at 200 and 850 hPa, respectively, in the tropical Indo-western Pacific during September-November 2004 observed and simulated by the 11 cumulus parameterization schemes. Comparison with observations shows that at 200 hPa (Fig. 3), experiments CPS2, CPS3 and CPS6 do not simulate the eastward propagation characteristics, experiments CPS1, CPS4, CPS7, and CPS10 do not simulate the continuous eastward propagation characteristics, experiments CPS8, CPS9 and CPS11 simulate a strong intensity, while experiment CPS5 simulates the eastward propagation characteristics of the MJO best. At 850 hPa (Fig. 4), experiments CPS1, CPS3, CPS4, and CPS6 do not simulate the eastward propagation characteristics, experiment CSP10 simulates a weak intensity, experiments CPS2, CPS5, CPS7, CPS8, and CPS11 simulate a strong intensity, and experiment CPS9 does not simulate the continuous eastward propagation characteristics.

Figure 5 gives the correlation coefficients between simulated results using the 11 cumulus parameterization schemes and observed zonal wind 30-60d component in terms of time-longitude maps. We can see that the model simulates the eastward propagation of the MJO component better in the lower troposphere than in the upper troposphere, but the simulation results of the eastward propagation of the MJO using different cumulus parameterization schemes differ, and most of the cumulus parameterization schemes cannot well characterize the eastward phenomenon of the MJO. Therefore, the WRF model basically cannot simulate the main characteristics of the MJO well, especially in terms of the eastward propagation and intensity of the MJO. Considering the prevalence of the cumulus parameterization scheme and the simulation effect of the eastward propagation of the MJO at 200 and 850 hPa, the CPS5 scheme is the best for the selected MJO eastward propagation cases, and the correlation coefficients of 200 and 850 hPa simulations with the observed 30-60d component of the tropical mean zonal winds distributions reach 0.70 and 0.74, in terms of time-longitude maps. In addition, the simulation results of CPS1, CPS7 and CPS11 are also better. In contrast, the worst simulation results are from CPS3, with the corresponding correlation coefficients of -0.35 and 0.50, respectively.

4. Nudging Simulation And Analysis Of Results
4.1 Experimental design

The nudging assimilation used in this paper works as follows: during the simulation, the simulated field in the model region is assimilated using the reanalysis field. The parameterization schemes of the physical process for the nudging simulation are the same as those used in Sect. 2.3.3, and the analysis field for nudging is also updated every six hours. Since experiments using different nudging coefficients show that the simulation results are not sensitive to the nudging coefficients, the nudging assimilation for CPS3 takes the default value of the model nudging coefficient 0.0003 for the analysis nudging simulation of the water-vapor field (Ndg_q).

4.2 Analysis of model results

Figure 6 shows the time-longitude maps of the 30-60d components of mean zonal winds at 200 and 850 hPa in the Indo-western tropical Pacific during September-November 2004 simulated by experiment Ndg_q. Comparing the results before and after the nudging of experiment CPS3, it can be seen that CPS3 does not simulate the eastward propagation characteristics of the MJO at 200 and 850 hPa (Fig. 3d, Fig. 4d), but after nudging of the water-vapor field, the results of Ndg_q show a significant improvement in terms of the eastward propagation of the MJO; the time-longitude correlation coefficients are 0.81 and 0.96 between simulations (Fig. 6a, Fig. 6b) and observations (Fig. 3a, Fig. 4a), respectively, which simulates better than experiment CPS5 for the MJO. The importance of the water vapor field in influencing the eastward propagation of the MJO zonal wind field is further explored below by comparing the evolution of the vertical profiles of the 30-60d component zonal wind, temperature, and specific humidity fields.

Figures 3a and 4a show the eastward propagation characteristics of the mean zonal winds at 850 hPa in the Indo-western Pacific region from 15 September to 15 October 2004. The period from 15 September to 15 October 2004 is thus chosen as the study period, and the altitude-longitude maps of the 30-60d components of the observed, CPS3, CPS5 and Ndg_q zonal winds, temperature and specific humidity are plotted every five days (Figs. 7, 8 and 9) to examine the phase evolution characteristics of each variable.

As seen in Fig. 7, due to the inappropriate cumulus parameterization scheme adopted in experiment CPS3, the simulated 30-60d component of the zonal wind at five-day interval shows different distribution characteristics throughout the troposphere from the observations; it not only fails to simulate the normal eastward propagation of the MJO, but even shows the westward propagation characteristics (the first and second columns of Fig. 7). Experiment Ndg_q, on the other hand, ensures that after the water-vapor distribution is assimilated, the atmospheric thermodynamic and dynamic adjustment processes make the 30-60d component of the zonal wind very similar to the observation (the last column of Fig. 7). The correlation coefficients of the 30-60d zonal wind component between the simulation and observation reach 0.52, 0.59, 0.47, 0.38, 0.54, 0.61, and 0.53 for these maps at 5-day interval, with a mean value of 0.52, while the corresponding correlation coefficients for experiment CPS5 (the third column of Fig. 7) are 0.44, 0.52, 0.42, 0.24, 0.41, 0.55, and 0.50, with a mean value of 0.44, which is smaller than the correlation coefficient values for experiment Ndg_q.
Figure 8 shows the height-longitude maps of the mean specific humidity 30-60d component corresponding to Fig. 7. It can be seen that the observations show the obvious eastward propagation of the MJO (the first column of Fig. 8). Since the water-vapor field is continuously nudged toward the observed field during the assimilation, experiment Ndg_q is able to simulate the eastward propagation of the specific humidity 30-60d component relatively well (the last column of Fig. 8), and experiment CPS5 is also able to simulate the eastward propagation of the specific humidity 30-60d component relatively well (the third column of Fig. 8), only that the simulation intensity too strong. However, experiment CPS3 gives completely inconsistent results, except that the simulated low-frequency disturbances are basically stationary most of the time, and their wavelength is only about 1/3 of the actual MJO wavelength (the second column of Fig. 8).

Comparing Figs. 7 and 8, we can see that the low-frequency propagation characteristics of water vapor and zonal wind are very similar, and the phases of both fields are basically the same: the positive perturbation zonal-wind region is accompanied by the positive perturbation water-vapor region. This is similar to the conclusion that the positive water-vapor anomaly in the mid troposphere has approximately the same phase as the MJO convection by Sperber (2003). However, the low-frequency perturbation of water vapor is 5–8 days ahead of the low-frequency perturbation of zonal wind; therefore, having sufficient water vapor in the eastward propagation of the low-frequency perturbation of zonal wind to produce wet convection to match the eastward propagation of the low-frequency perturbation of zonal wind may be a factor for the eastward propagation of the low-frequency perturbation of zonal wind. Li (1985) first introduced the conditional instability of the second kind (CISK) theory into the study of atmospheric low-frequency oscillations, and proposed a cumulus convective heating feedback mechanism for tropical atmospheric low-frequency oscillations. Lau and Peng (1987) introduced mobile wave-CISK as the generation mechanism of tropical low-frequency oscillations, which can better explain the slow eastward propagation of tropical atmospheric MJO along the equator. All these theoretical works clarify the role of tropical wet convection in the generation and propagation of the MJO, and the sensitivity experiments in this paper provide verification for these theories. In addition, the presence of a westerly dip of the low-frequency components of water vapor and zonal winds throughout the troposphere, that is, the zonal asymmetric distribution with respect to the tilting axis, confirms that a suitable water-vapor distribution is a key factor to ensure the observed eastward propagation of the tropical atmospheric MJO, as pointed out by Hsu and Li (2012).

Figure 9 shows the height-longitude maps of mean temperature 30-60d component, corresponding to Fig. 7. Although Fig. 9 also presents the observed eastward propagation characteristics of the low-frequency temperature perturbation (the first column of Fig. 9), its spatial structure is relatively complex compared to the eastward propagation characteristics of the zonal wind (the first column of Fig. 7) and specific humidity (the first column of Fig. 8) low-frequency perturbations; and the intensity of the perturbation shows irregular variation in both horizontal and vertical directions. Similarly, both experiments CPS5 (the third column of Fig. 9) and Ndg_q (the last column of Fig. 9) can simulate the eastward propagation of low-frequency temperature perturbations, but the average correlation coefficients of the simulated and observed intensity distributions of temperature low-frequency perturbations on the altitude-longitude
maps at different moments are only 0.14 and 0.28, respectively, much smaller than the corresponding correlations coefficients of specific humidity and zonal winds. In contrast, experiment CPS3 (the second column of Fig. 9) does not simulate the eastward propagation characteristics of the temperature low-frequency disturbance as observed.

In addition, similar to experiment Ndg_q that nudges only specific humidity, temperature is also nudged in experiment CPS3, but the analysis of the results shows that the temperature nudging assimilation only improves the low-frequency propagation characteristics of temperature to a large extent, and the effects on the low-frequency zonal wind and low-frequency specific humidity in terms of eastward propagation characteristics do not improve significantly (figure omitted). Therefore, temperature distribution is not a key factor to control the low-frequency MJO eastward propagation compared to humidity distribution.

### 4.3 Mechanism analysis

From Fig. 8, it can be seen that there is a zonal asymmetry in the specific humidity field relative to the tilting axis during the evolution from 15 September to 15 October. To demonstrate the importance of atmospheric stability in the propagation of the MJO, we investigate the role of water vapor in influencing the propagation of the MJO via affecting atmospheric stability by examining the evolution of equivalent potential temperature $(\theta_e)$.

$(\theta_e)$ is determined by both temperature and humidity. If the atmosphere is initially moist but unsaturated and
\[
\frac{\partial \theta_e}{\partial z} < 0
\]
the atmosphere is potentially unstable. If such atmosphere reaches saturation by sufficient lifting, the entire atmosphere column becomes unstable (Li and Wang 1994). Figure 10 shows the height-longitude maps of the 30-60d component of $(\theta_e)$ corresponding to Fig. 7. It shows that both observations and simulations are similar to water vapor in terms of the low-frequency characteristics (Fig. 8), and differ significantly from the low-frequency characteristics of temperature (Fig. 9). The difference of the 30-60d component of $(\theta_e)$ variation with height from 925 to 775 hPa is defined as the 30-60d component of the convective instability parameter at 850 hPa. The time-longitude maps of the observation and experiments CPS3, CPS5 and Ndg_q of the tropical mean convective instability parameter in the Indo-western Pacific region during September-November 2004 are plotted (Fig. 11). The convective instability parameter (Fig. 11a) shows eastward propagation, but compared to the 850 hPa zonal wind (Fig. 1b), the propagation is not continuous and there are some westward propagation periods. Experiment CPS3 (Fig. 11b) shows westward propagation contrary to the observation. Experiment CPS5 (Fig. 11c) simulates part of the eastward propagation, but the simulation degrades to the east of 80°E. Experiment Ndg_q (Fig. 11d) can basically simulate the eastward propagation of the low-frequency convective instability parameter at 850 hPa, but the simulated intensity is weak in some periods. These experimental results indicate that the water-vapor field can maintain the MJO propagation by affecting the atmospheric stability, while the temperature field has little effect on the MJO eastward
propagation, so enhancing the model's simulation effect on atmospheric stability plays an important role in improving the simulation of MJO eastward propagation.

The convective instability parameter at 850 hPa (Fig. 11a) and the time-longitude map of zonal wind (Fig. 1b) show that the low-frequency propagation characteristics of both are similar, but there is a lead-lag relation in time. Figure 12 shows the time-lag correlation characteristics between the four mean convective instability parameters given in Fig. 11 and the 30-60d component time-longitude maps of the observed zonal wind (Fig. 1b). The correlation coefficient is the largest when the observed convective instability parameter is ahead of the zonal wind by 6–7 days (Fig. 12a), which is consistent with the water-vapor low-frequency disturbance estimated from Figs. 7 and 8 being ahead of the zonal wind low-frequency disturbance by 5–8 days, again demonstrating that the water-vapor field can contribute to the propagation of the MJO by affecting the atmospheric stability and that the tropical wet convection located east of the MJO disturbance plays a key role. The simulated results of experiment Ndg_q are the closest to the observations, but the correlation coefficient between the two is the greatest when the convective instability parameter is ahead of the zonal wind by about 10 days (Fig. 12d). Although the simulated results of experiment CPS5 are better than those of experiment CPS3, the simulated results of CPS5 also do not portray the evolution of the convective instability parameter well. The convective instability parameter is ahead of the zonal wind by about 18 days (Fig. 12c), while the simulated convective instability parameter of experiment CPS3 even lags behind the zonal wind by 3–4 days (Fig. 12b). Figure 12a also shows that the correlation coefficient is the greatest when the convective instability parameter overtakes the zonal wind by 6–7 days, while the negative correlation is the greatest when it lags the zonal wind by 13–14 days, that is, convective instability exists in the lower troposphere 6–7 days before the occurrence of the low-level easterly anomaly and 13–14 days after the occurrence of the westerly anomaly. This confirms the finding of Maloney (2009), that is, column-integrated MSE accumulates before intraseasonal precipitation prior to the onset of low-level easterly anomalies, while MSE releases energy during and after precipitation during the onset of westerly anomalies.

5. Conclusions

In this study, we focus on the eastward propagation of the MJO in the tropical atmosphere from the Indian Ocean to the western Pacific Ocean in the autumn of 2004 (September-November). The nudging assimilation of the WRF model is used to conduct sensitive tests of the role of water vapor in the eastward propagation of the MJO. The role of water-vapor disturbance in the eastward propagation of the MJO is revealed by comparing the simulation results with observations. The following conclusions are obtained.

The regional climate model is sensitive to the cumulus parameterization scheme to simulate the eastward propagation of the MJO. An unsuitable scheme will not simulate the eastward propagation of the MJO at all. For the individual cases of MJO eastward propagation studied here, the Tiedtke scheme can simulate the MJO eastward propagation well, while the Grell-Freitas scheme nearly has no skill.
When using the Grell-Freitas scheme and the water-vapor field in the model is simulated by assimilating the observation, the model will be able to describe the eastward propagation of MJO better. Moreover, the low-frequency water-vapor phase is ahead of the zonal-wind phase. In contrast, nudging simulations of temperature in the model cannot reasonably produce the eastward propagation of the MJO, which confirms that only the tropical atmospheric water-vapor distribution is the main factor determining the eastward propagation of the MJO.

The evolution characteristics of equivalent potential temperature and specific humidity during the MJO propagation are basically consistent, and both show a westerly dip, that is, a zonal asymmetry with respect to the tilting axis, while there are large differences with the evolution characteristics of the temperature field. After nudging the water-vapor field in the model domain, the simulated effect of the convective instability parameter on the MJO at 850 hPa is enhanced, and it is 6–7 days ahead of the zonal wind. Therefore, the water-vapor field affects the propagation of the MJO by influencing the atmospheric stability, while temperature has little effect on the eastward propagation of the MJO.

Declarations

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**Tables**

**Tab. 1** Names of the 11 experiments and their corresponding cumulus parameterization schemes

| Exp   | Cumulus parameterization scheme                                      |
|-------|---------------------------------------------------------------------|
| CPS1  | Kain-Fritsch (Kain 2004)                                            |
| CPS2  | Betts-Miller-Janjic (Janjic 1994)                                    |
| CPS3  | Grell-Freitas (Grell and Freitas 2014)                               |
| CPS4  | Grell-3 (Grell 1993; Grell and Devenyi 2002)                         |
| CPS5  | Tiedtke (Tiedtke 1989; Zhang et al. 2011)                            |
| CPS6  | Zhang-McFarlane (Zhang and McFarlane 1995)                           |
| CPS7  | KF-CuP (Berg et al. 2013)                                           |
| CPS8  | New SAS (Han and Pan 2011)                                          |
| CPS9  | New Tiedtke (Zhang and Wang 2017)                                   |
| CPS10 | Grell-Devenyi (Grell and Devenyi 2002)                               |
| CPS11 | Old Kain-Fritsch (Kain and Fritsch 1990)                             |

**Figures**
Figure 1

Time-longitude maps of the 30-60d components (m s$^{-1}$) of mean zonal winds in the Indo-west Pacific (30°-130°E) tropics (10°S-10°N) at 200 hPa (a) and 850 hPa (b) in September-November 2004.

Figure 2

Model domain
Figure 3

Time-longitude maps of observed and simulated mean 200 hPa zonal wind's 30-60d components (m s⁻¹) in the Indo-western Pacific (30°-130°E) tropics (10°S-10°N) during September-November 2004 a: Observation; b: CPS1; c: CPS2; d: CPS3; e: CPS4; f: CPS5; g: CPS6; h: CPS7; i: CPS8; j: CPS9; k: CPS10; l: CPS11
Figure 4

Same as Fig. 3, but for 850 hPa
Figure 5

Correlation coefficients between observations and simulations for 30-60d component time-longitude profiles of zonal winds at 200 hPa (blue) and 850 hPa (red) using 11 cumulus parameterization schemes (CPS1-CPS11)
Figure 6

Time-longitude maps of 30-60d components of the mean zonal winds at 200 hPa (a) and 850 hPa (b) in the Indo-western Pacific (30°-130°E) tropics (10°S-10°N) for September-November 2004 simulated by experiment Ndg_q
Figure 7

Height-longitude maps of 30-60d component (m s⁻¹) of the mean zonal winds in the Indo-western Pacific (30°-130°E) tropics (10°S-10°N) for the 5-day interval from 0000 UTC 15 September to 0000 UTC 15 October a1-a7: Observation; b1-b7: CPS3; c1-c7: CPS5; d1-d7: Ndq_q
Figure 8

Same as Fig. 7, but for meridional-mean specific humidity (kg kg⁻¹)
Figure 9

Same as Fig. 7, but for meridional-mean temperature (in K)
Figure 10

Same as Fig. 7, but for equivalent potential temperature (K)
Figure 11

Time-longitude maps of the 30-60d component of the mean convective instability parameter (K m⁻¹) over the Indo-western Pacific (30°-130°E) tropics (10°S-10°N) at 850 hPa in September-November 2004: observations (a) and simulated results by CPS3 (b), CPS5 (c) and Ndg_q (d).

Figure 12

Time lag correlation coefficients of observation (a) and simulated results by CPS3 (b), CPS5 (c) and Ndg_q (d) between time-longitude maps of 30-60d components of observed zonal winds (Fig. 1b) and
mean convective instability parameters over the Indo-western Pacific (30°-130°E) tropics (10°S-10°N) at 850 hPa in September-November 2004