MJO and Convectively Coupled Equatorial Waves Simulated by CMIP5 Climate Models

MENG-PAI HUNG,* JIA-LIN LIN,+ WANQIU WANG,† DAEHYUN KIM,‡ TOSHIAKI SHINODA,§ AND SCOTT J. WEAVER#

* Climate Prediction Center, NOAA/NWS/NCEP, College Park, Maryland, and Wyle Information Systems LLC, McLean, Virginia
† Department of Geography, The Ohio State University, Columbus, Ohio
‡ Climate Prediction Center, NOAA/NWS/NCEP, College Park, Maryland
§ Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York
# Naval Research Laboratory, Stennis Space Center, Mississippi, and Department of Physical and Environmental Sciences, Texas A&M University–Corpus Christi, Corpus Christi, Texas

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ABSTRACT

This study evaluates the simulation of the Madden–Julian oscillation (MJO) and convectively coupled equatorial waves (CCEWs) in 20 models from the Coupled Model Intercomparison Project (CMIP) phase 5 (CMIP5) in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and compares the results with the simulation of CMIP phase 3 (CMIP3) models in the IPCC Fourth Assessment Report (AR4). The results show that the CMIP5 models exhibit an overall improvement over the CMIP3 models in the simulation of tropical intraseasonal variability, especially the MJO and several CCEWs. The CMIP5 models generally produce larger total intraseasonal (2–128 day) variance of precipitation than the CMIP3 models, as well as larger variances of Kelvin, equatorial Rossby (ER), and eastward inertio-gravity (EIG) waves. Nearly all models have signals of the CCEWs, with Kelvin and mixed Rossby–gravity (MRG) and EIG waves being especially prominent. The phase speeds, as scaled to equivalent depths, are close to the observed value in 10 of the 20 models, suggesting that these models produce sufficient reduction in their effective static stability by diabatic heating. The CMIP5 models generally produce larger MJO variance than the CMIP3 models, as well as a more realistic ratio between the variance of the eastward MJO and that of its westward counterpart. About one-third of the CMIP5 models generate the spectral peak of MJO precipitation between 30 and 70 days; however, the model MJO period tends to be longer than observations as part of an overreddened spectrum, which in turn is associated with too strong persistence of equatorial precipitation. Only one of the 20 models is able to simulate a realistic eastward propagation of the MJO.

1. Introduction

Tropical convection is often organized into synoptic-to planetary-scale disturbances whose time scale is less than a season (~90 days) (Wheeler and Kiladis 1999, hereafter WK; Wheeler and Weickmann 2001). This “subseasonal” variability plays an important role in the global climate system by modulating the location and timing of tropical deep convection and has been suggested as a key source of untapped predictability for the extended-range forecasts in both the tropics and extratropics (e.g., Schubert et al. 2002; Waliser et al. 2003a). Most of the dominant convective tropical intraseasonal modes are solutions of the shallow water model (Matsuno 1966), with a modified equivalent depth (WK). These so-called convectively coupled equatorial waves (CCEWs) include Kelvin, equatorial Rossby (ER), mixed Rossby–gravity (MRG), eastward inertio-gravity (EIG), and westward inertio-gravity (WIG) waves (Takayabu 1994; WK; Kiladis et al. 2009). In addition to these waves, there exists another mode of the tropical intraseasonal variability, the Madden–Julian oscillation (MJO; Madden and Julian 1971; Zhang 2005). The MJO involves the interaction between the convection and large-scale circulation and is characterized by the eastward
propagation of planetary-scale (wavenumber 1–3) and low-frequency (period 30–60 days) waves.

The MJO and CCEWs strongly affect the tropical weather such as the onset and breaks of the Asian and Australian monsoon systems (e.g., Yasunari 1979; Wheeler and McBride 2005) and the frequency of tropical cyclone formations in all ocean basins (e.g., Liebmann et al. 1994; Maloney and Hartmann 2001; Besafi and Wheeler 2006; Klotzbach 2010; Schreck and Molinari 2011). On longer time scales, they are influential in the triggering and termination of El Niño–Southern Oscillation (ENSO) events (Kessler et al. 1995; Takayabu et al. 1999; Bergman et al. 2001). Consistently, ENSO prediction has been shown to be strongly modulated by intraseasonal variability in the initial state (Wang et al. 2011). As a strong tropical heating source, the MJO also drives teleconnections to the extratropics affecting precipitation events in North and South America (e.g., Mo and Higgins 1998; Jones and Schemm 2000; Jones et al. 2004) through its influence on the Arctic and Antarctic Oscillations (Miller et al. 2003; Carvalho et al. 2005; L’Heureux and Higgins 2008). The MJO also has been suggested as a key source of untapped predictability for the extended-range forecast in both the tropics and extratropics (e.g., Schubert et al. 2002; Waliser et al. 2003a).

Unfortunately, the simulation of tropical intraseasonal variability continues to be burdensome and improvement has been a difficult task for the last several generations of general circulation models (GCMs; Slingo et al. 1996; Lin et al. 2006; Zhang et al. 2006; Sperber and Annamalai 2008; Kim et al. 2009; Weaver et al. 2011). Factors that affect MJO simulation are typically related to the cumulus parameterization and include the moisture convective trigger (e.g., Wang and Schlesinger 1999; Lin et al. 2008; Kim and Kang 2012; Kim et al. 2012), diluted CAPE closure (Subramanian et al. 2011; Zhou et al. 2012), interactions between deep and shallow convection (Zhang and Song 2009), interactions between deep convection and stratiform precipitation (Fu and Wang 2009; Seo and Wang 2010), the vertical heating profile (Li et al. 2009), convective momentum transport (Deng and Wu 2010; Zhou et al. 2012), cloud–radiation feedback (Lin et al. 2007; Kim et al. 2011a), and the time-mean state (Sperber and Annamalai 2008; Kim et al. 2009). The continued lack of success of MJO simulations among GCMs is surprising given that various studies have shown which aspects of GCM configuration are important for increased simulation fidelity. Such a paradoxical situation is likely due to the fact that improving the MJO simulation is not the only goal of GCM development. Based on atmospheric GCM simulations, Kim et al. (2011a) showed that the mean state may be degraded with changes in cumulus parameterization that lead to a better simulation of the MJO in GCMs. This suggests that configurations for improving MJO simulations may not be necessarily adopted in GCMs that participate in official programs since the mean state is degraded. Nevertheless, given the poor MJO simulation in the former generations of the GCMs, tracking the fidelity of MJO simulation in the new generation of the state-of-the-art GCMs is of great interest in both MJO science and climate modeling communities.

In preparation for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), nearly two dozen international climate modeling centers have conducted simulations for the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The CMIP5 simulations include a comprehensive set of long-term simulations of both the twentieth-century climate and various climate change scenarios for the twenty-first century. Since the Fourth Assessment Report (AR4) and phase 3 of the Coupled Model Intercomparison Project (CMIP3), modeling groups have invested mightily in efforts to develop their climate models. As a result, the CMIP5 models on average have higher horizontal resolutions than those in CMIP3 and have improved subgrid-scale parameterizations that have been newly developed or revised from that used in the CMIP3 version. Some of the CMIP5 models have also evolved from “climate system models” to “Earth system models” and include biogeochemical components and time-varying carbon fluxes among the ocean, atmosphere, and terrestrial biosphere. The evaluation of the performance of the CMIP5 models in terms of the tropical intraseasonal variability and the comparison of the simulation fidelity against that of the former generation of models is the goal of this study.

The evaluation of the tropical intraseasonal variability simulated in 14 of the CMIP3 models was conducted in Lin et al. (2006). To facilitate an objective comparison with that study, we will strictly follow their methodology here. First we summarize the main findings of Lin et al. (2006) to provide reference points in our evaluation in the following sections. They found that 1) the total intraseasonal (2–128 day) variance of precipitation is too weak in most of the models; 2) about half of the models have signals of CCEWs, with Kelvin and MRG–EIG waves especially prominent; 3) variance of the CCEWs is too weak for all wave modes except the EIG wave; 4) phase speeds of the CCEWs are too fast and are consistent within a given model across modes; 5) only 2 out of the 14 models simulate observed MJO variance while the variance is less than half of the observed value in others; 6) the ratio between the eastward MJO variance and the variance of its westward counterpart is too small in a
majority of the models; and 7) the MJO variance in 13 of
the 14 models is not derived from a pronounced spectral
peak but rather comes as a result of an overredden spectrum, which is associated with too strong persistence
of equatorial precipitation.

The models and validation datasets used in this study
are described in section 2. The diagnostic methods are
described in section 3. Results are presented in section 4.
A summary and discussion are given in section 5.

2. Models and validation datasets

Since Lin et al. (2006) used eight years of the simu-
lations in CMIP3, we employ the same length (8 yr) of
historical simulations from 20 coupled GCMs in CMIP5
to compare directly with CMIP3 results. The names and
abbreviations of models used in this study are listed in
Table 1. Daily mean surface precipitation from all
models is analyzed, and the model results are compared
with the analysis of multiple observational datasets.
Since there are uncertainties associated with precipi-
tation measurements/retrievals, we use two different
precipitation datasets (as in Lin et al. 2006) that cover
eight years from 1997 to 2004. These are the Geosta-
tionary Operational Environment Satellite (GOES)
Precipitation Index (GPI; Janowiak and Arkin 1991)
and the Global Precipitation Climatology Project (GPCP)
1° daily (1DD) precipitation (Huffman et al. 2001).
We use GPI daily precipitation with a horizontal resolution
of 2.5° latitude by 2.5° longitude, which is retrieved
based on infrared (IR) measurements from multiple
geosynchronous satellites. The GPCP data provide daily
precipitation with a horizontal resolution of 1° lon-
titude by 1° latitude.

3. Method

Since most methods used in this study are nearly iden-
tical to those used in the study of Lin et al. (2006), which
evaluated the CMIP3 models, we describe the procedure
of the analysis only briefly in this section. Further details
are found in Lin et al. (2006) and WK. First, following the
methodology of WK, wavenumber–frequency spectra of
daily tropical precipitation were computed from the eight
years of model outputs and observed data from the GPI
and 1DD datasets. These precipitation time series were
first averaged over each 5° longitude bin and then further
averaged over the latitudinal bands of 0°–15°N and 0°–
15°S. Then the symmetric component, which is defined as
the sum of the 0°–15°N mean and 0°–15°S mean divided
by 2, and the antisymmetric component, which is defined
as the difference between the 0°–15°N mean and 0°–15°S
mean divided by 2, were calculated. The space–time
spectra were then computed for both the symmetric and
antisymmetric components.

Second, Kelvin, ER, MGR, EIG, and WIG modes, as
defined by WK (see their Fig. 6), were isolated using the
same method. The time series of each mode was obtained
by filtering in the wavenumber–frequency domain (see
Fig. 6 of WK for the defined regions of filtering for each
wave) and an inverse space–time Fourier transform. Fi-
nally, the MJO, which is defined as significant rainfall
variability in eastward wavenumbers 1–6 and in the
period of 30–70 days, was isolated. We first used an
inverse space–time Fourier transform to obtain the
time series of the eastward wavenumber 1–6 com-
ponent for all available frequencies. These time series
were then filtered using a 365-point 30–70-day Lanczos
filter [Duchan 1979; see Fig. 2 of Lin et al. (2006) for the
response function]. As a result of the time domain fil-
tering, 182 days of data were lost at each end of the time
series (364 days in total). The anomaly time series
for the time–space domain of eastward wavenumber
1–6 and 30–70–day period is referred to as the MJO
anomaly hereafter. Its westward counterpart, which is
the westward wavenumber 1–6, 30–70–day anomaly, is
also computed using the same method and then com-
pared to the MJO anomaly.

It should be noted here that this study focuses solely
on the intraseasonal variability, which propagates east-
ward and amplifies to a seasonal maximum on the
equator in boreal winter and spring, when climato-
logical convection and warm SST cross the equator
(Salby and Hendon 1994; Zhang and Dong 2004;
Wheeler and Hendon 2004), and that the boreal summer
intraseasonal oscillation (BSIO; e.g., Yasunari 1979;
Knutson et al. 1986; Kembul-Cook and Wang 2001;
Lawrence and Webster 2002; Straub and Kiladis 2003;
Waliser et al. 2003b; and many others), which has
a major northward propagating component and has its
maximum variance in the Asian monsoon region, is not
a subject of this study.

4. Results

a. Climatological precipitation in the equatorial belt

Intraseasonal variability strongly depends on the mean
background state (WK; Hendon et al. 1999; Inness et al.
2003; Kim et al. 2009). To compare the time-mean con-
vective intensity, the sum of zonal wavenumbers 0–6 of
annual mean rainfall rate averaged between 15°S and
15°N is shown in Fig. 1 for all models analyzed in this
study as well as two observational estimates. The en-
semble mean of all models is included in Fig. 1 for
CMIP5 and CMIP3 simulations. Similar to the CMIP3
<table>
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<th>Institute</th>
<th>Model name (IPCC identification)</th>
<th>Resolution</th>
<th>Vertical levels/layers (model top)</th>
<th>Deep convection scheme/modification</th>
<th>Convective closure/trigger</th>
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<td>Canadian Centre for Climate Modelling and Analysis (CCCma)</td>
<td>Fourth Generation Canadian Coupled Global Climate Model (CanCM4)</td>
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<td>Spectral T63 35 (1 hPa)</td>
<td>Zhang and McFarlane (1995)</td>
<td>CAPE</td>
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<td>Second Generation Canadian Earth System Model (CanESM2)</td>
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<td>Moisture convergence</td>
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<td>Gregory and Rowntree (1990)/Gregory (1995)</td>
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<td>Model for Interdisciplinary Research on Climate (MIROC), version 4 (high resolution) (MIROC4h)</td>
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<td>Resolution</td>
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<td>Vertical levels/layers (model top)</td>
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<td>Spectral T42 (2.8')</td>
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<td>Gregory and Rowntree (1990)</td>
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<td>26</td>
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models, those from the CMIP5 reproduce the basic features of observed precipitation, with primary maxima over the Indo-Pacific warm pool region and two secondary maxima over Central/South America and Africa. The magnitude of the precipitation over the warm pool in all models is close to that in the observations. Compared to the CMIP3 models, the CMIP5 models show slight improvement over the eastern Indian Ocean. However, within the warm pool region, only five models (CanESM2, CanCM4, CSIRO, INM-CM4, and FGOALS; all model names are provided in full in Table 1) reproduce the local minimum of precipitation over the Maritime Continent. Outside of the warm pool region, the most common bias for the CMIP3 models was excessive rainfall throughout the eastern Pacific and insufficient rainfall over Central/South America. These biases still exist in most of the CMIP5 models.

When the precipitation average is narrowed to between 5°N and 5°S, the CMIP5 models show more variability in their performance, especially over the Indo-Pacific warm pool (Fig. 1b). Some models (e.g., IPSL-5BL, MIROC4h, HadG2-ES, and MRI3) show a greater value of precipitation over the western Pacific than over the eastern Indian Ocean. In contrast, several other models (CSIRO, INM-CM4, IPSL-5AL, and IPSL-5AM) show too strong precipitation over the eastern Indian Ocean and too weak precipitation over the western Pacific, which is significantly smaller than their corresponding 15°N–15°S average (Fig. 1a). This is a result of the double-ITCZ pattern (Lin et al. 2007) in their horizontal distributions (not shown), and the problem is more severe in the CMIP5 simulations than in the CMIP3 models. Off the equator in the warm pool region, all models produce much larger precipitation than observations over the western Indian Ocean and eastern Pacific, and all models except CSIRO simulate excessive precipitation over the Atlantic Ocean.

In short, the climatological precipitation over the Indo-Pacific warm pool is reasonably simulated by the CMIP5 climate models, except that several models (CSIRO, INM-CM4, IPSL-5AL, and IPSL-5AM) produce too little precipitation on the equator in the western Pacific because of their double-ITCZ problem. Overall, the model-ensemble average of CMIP5 is similar to that of CMIP3 and continued improvement is needed, especially for the simulations in the western Indian Ocean, eastern Pacific, South America, and the Atlantic Ocean.

b. Total intraseasonal (2–128 day) variance and raw space–time spectra

Figures 2a and 2b show the total variance of the 2–128-day precipitation anomaly along the equator averaged between 15°N and 15°S and between 5°N and 5°S, respectively. It is interesting to see that most of the models faithfully represent the Indonesian minimum in variability, even those that do not have a local minimum in precipitation. The CMIP5 models generally simulate larger total intraseasonal variance than the CMIP3 models. For example, a large fraction of the CMIP5 models produce a total 15°N–15°S average variance greater than 10 (mm day$^{-1}$)$^2$ in the eastern Indian Ocean and western Pacific (Fig. 2a). However, for CMIP3 only one model simulated the 15°N–15°S average variance greater than 10 (mm day$^{-1}$)$^2$ in the same regions (Lin et al. 2006). The CMIP5 models tend to have larger variance over the western Pacific than over the Indian Ocean, which is consistent with their tendency to have larger annual mean precipitation there (Fig. 1) and was also a feature for the CMIP3 models.

![Fig. 1. Annual mean precipitation along the equatorial belt averaged between (a) 15°N and 15°S and (b) 5°N and 5°S for two observational datasets and 20 models. The data are smoothed zonally to retain only wavenumbers 0–6.](image-url)
Figure 3 shows the raw symmetric wavenumber–frequency power spectra of equatorial precipitation, plotted in log scale. Only spectra of the symmetric component are presented, as the characteristics of the antisymmetric spectra are similar to those of the symmetric spectra. Here we compare the magnitude of relatively shorter and longer time scale components, since the amplitude of CCEWs and MJO will be discussed in detail in the following sections. A majority of models underestimate the variance of high-frequency components (period < 6 days) although a few models (CanESM2, CanCM4, CNRM-CM5, and MIROC4h) have powers comparable to observation at this time scales.

Regarding the longer time scale (periods > 30 days), about half of the models (CNRM-CM5, CSIRO, IPSL-5BL, FGOALS, MIROC5, HadCM3, MPI-E-L, MR13, and NorE1-M) exhibit power that is comparable to the observations, while others underestimate the low-frequency power. These nine models tend to simulate a stronger eastward power than westward at the MJO time scale, suggesting that the simulation of a realistic...
Fig. 3. Space–time spectrum of the 15°N–15°S symmetric component of precipitation. Frequency spectral width is 1/128 cpd.
Fig. 3. (Continued)
amplitude of low-frequency variability is related to the simulation of the MJO.

c. Dominant intraseasonal modes

In Figs. 4 and 5, symmetric and antisymmetric MJO and CCEWs are identified by removing background spectra from the raw symmetric and antisymmetric spectra, respectively. The background spectrum (WK) is calculated for each model and therefore is model dependent. Some notable improvements of the CMIP5 models over the CMIP3 models in simulating the signals of MJO and CCEWs are observed in these figures.
Specifically, in contrast to the CMIP3 models where only half of models were able to represent the signature of the CCEWs (Lin et al. 2006), almost all CMIP5 models are able to simulate CCEWs. This is especially true for the Kelvin and the MRG–EIG waves although the Kelvin wave signal is not distinctive in CSIRO and IPSL-5BL and the MRG–EIG waves are not well simulated by INM-CM4 and IPSL-5AM. Moreover, the equivalent depth of the waves, which was too high in most of the CMIP3 models (Lin et al. 2006), is close to the observed value of 25 m in half of the 20 models (CanESM2, CanCM4, CCSM4, FGOALS, MIROC5, HadCM3, HadG2-CC, HadG2-ES, MPI-E-L, and NorE1-M). In five models (INM-CM4, IPSL-5AL, IPSL-5AM, MIROC-E, and MIROC-EC), the equivalent depth is still too deep, while it is too shallow in two models (CNRM-CM5 and MRI3). The equivalent depth of a wave is proportional to the effective static stability felt by the wave, which is reduced when diabatic heating compensates adiabatic cooling in the upward branch of the wave. The models that exhibit a reasonable equivalent depth are producing a large enough reduction in their effective static stability from diabatic heating, while the reduction is extreme in the models with too low equivalent depth. As in the CMIP3 models, the equivalent depth of the CCEWs is consistent within one model. About half of the CMIP5 models (CNRM-CM5, CSIRO, IPSL-5AL, IPSL-5BL, MIROC5, HadCM3, MPI-E-L, MRI3, and NorE1-M) exhibit the spectral peak of the MJO to some extent (Fig. 4). Powers of eastward propagating components near the MJO spatial and temporal scale in these models are more distinctive than that of westward propagating counterparts. This is encouraging when compared to the results of CMIP3 models, where 4 out of 14 models showed such features (Lin et al. 2006).

Through the space–time spectral analysis in Figs. 4 and 5, when a model displays signals of a certain wave mode, it means that the variance of that wave mode stands out above the background spectra (i.e., a high signal-to-noise ratio), but the absolute value of the variance of that wave may not be large. In addition to the signal-to-noise ratio, the absolute value of the variance is also important because it represents the power of that wave mode, and will affect the strength of associated circulation signals and teleconnections. Therefore, it is interesting to look at the absolute values of the variance of each wave mode and compare them with observations. Figures 6a–e show the variances of the Kelvin, ER, MRG, EIG, and WIG modes along the equator averaged between 15°N and 15°S. Note that the absolute value of the variance of a wave mode is meaningful only when the signal-to-noise ratio of that wave mode is high, which can be checked in Figs. 4 and 5. For the Kelvin mode in CMIP5 (Fig. 6a), some models (CCSM4, CNRM-CM5, FGOALS, MIROC4h, MIP-E-L, MRI3, and NorE1-M) capture the observed longitudinal distribution, while the rest of models show too weak variance associated with this eastward wave mode. On average, both CMIP5 and CMIP3 are too weak compared to the observation, although the CMIP5 average variance appears to be slightly larger than the CMIP3 average in the central-eastern Pacific (180°–290°E). For the ER mode (Fig. 6b), two models (FGOALS and MPI-E-L) from CMIP5 faithfully reproduce the observed magnitude and longitudinal distribution of the variance. Meanwhile, the most of models show weak variances lower than 1 mm day\(^{-1}\). For the average of all models, compared to CMIP3, the CMIP5 produces larger variances than the CMIP3 over the Indo-Pacific warm pool with an increase of 47% of the variance averaged between 65° and 185°E. For the MRG mode (Fig. 6c), which is important for tropical cyclone genesis, both of CMIP5 and CMIP3 models reproduce too small variances although their largest amplitudes are located over the Indo-Pacific region, which is same as in observations. This indicates that the GCMs are still challenged in simulating this particular wave mode. For the EIG mode (Fig. 6d), there is large scatter in the simulated variances. Only three models (CNRM-CM5, IPSL-5AM, and HadG2-ES) produce nearly realistic magnitude and are able to capture the observed double maxima over the warm pool region. Several models (IPSL-5BL, FGOALS, MPI-E-L, and MRI3) produce overly strong variances, while others (e.g., INM-CM4, IPSL-5AL, MIROC-E, and MIROC-EC) simulate overly weak variances. The CMIP5 model average shows variances comparable to the CMIP3 average. For the WIG mode (Fig. 6e), all models simulate too weak variance except CNRM-CM5, which produces nearly realistic variance over the western Pacific.

**d. Variance of the MJO mode**

In this section, the focus shifts to the MJO mode, specifically the daily variance in the MJO window of eastward wavenumbers 1–6 and periods of 30–70 days. Figure 7a shows the variance of the MJO anomaly along the equator averaged between 15°N and 15°S. Note that the absolute value of the MJO variance is meaningful only when the signal-to-noise ratio of the MJO mode is high, which can be checked in Fig. 4 and will also be shown later in Fig. 10. For CMIP3, there were only 2 models out of 14 models with MJO variance larger than half of the observed values, while for CMIP5 7 out of 20 models (CNRM-CM5, CSIRO, IPSL-5BL, FGOALS,
FIG. 4. Space–time spectrum of the 15°N–15°S symmetric component of precipitation divided by the background spectrum. Superimposed are the dispersion curves of the odd meridional mode numbered equatorial waves for the three equivalent depths of 12, 25, and 50 m. Frequency spectral width is 1/128 cpd.
FIG. 4. (Continued)
MRI-3, MIROC5, and MPI-E-L) exhibit an MJO variance larger than half of the observed values over eastern Indian Ocean and/or western Pacific. Most models produce the maximum variance over the eastern Indian Ocean. For the average of all models, the CMIP5 produces larger MJO variance than the CMIP3 over the Indo-Pacific region, with an increase of 23% variance between 65° and 185°E (Fig. 7a). This is a significant improvement for the global climate models since too weak precipitation variance in the MJO wavenumber–frequency
band has been a long-standing problem in GCMs, despite the fact that many of these models have reasonable values of zonal wind variance, which is fundamental to MJO-related low-level moisture convergence and associated coupled convection in observations. From the viewpoint of weather and climate prediction, a realistic MJO precipitation signal is highly desirable because it is the latent heat released by precipitation that drives teleconnections to the subtropics and extratropics and leads to useful intraseasonal predictability in these regions.

Although the CMIP5 models have an improved performance in MJO variance over there CMIP3 counterparts between 15°N and 15°S, a previous study (Wang and Rui 1990) indicated that eastward-propagating MJO precipitation events occur most often on the equator, with the frequency of occurrence decreasing away from the equator. Therefore, it is of interest to see how well the models can capture equatorial maximum of MJO variance in an area closer to the equator. Figure 7b is same as Fig. 7a, but for precipitation averaged between 5°N and 5°S. Both of the two observational datasets show that the variance of the 5°N–5°S average is approximately twice as large as that of the 15°N–15°S average. For CMIP5, CNRM-CM5 and IPSL-5BL produce very realistic MJO precipitation variance, with the variance of CNRM-CM5 in particularly good agreement with the GPI dataset throughout the entire Indian Ocean and the western Pacific. Three other models (CSIRO, MPI-E-L, and MR13) also simulate large MJO variance close to the equator, although the models with a double-ITCZ pattern produce large variance only over the Indian Ocean, not the western Pacific. Similar to the result in the 15°N–15°S range, the average of the CMIP5 models is about 25% greater than that of the CMIP3 models over the Indo-Pacific region (65°–185°E). In addition, the difference throughout the Indian Ocean between CMIP5 and CMIP3 averages over 5°N–5°S is even larger than that over 15°N–15°S. This implies that the CMIP5 models substantially have better MJO capability than CMIP3 in its most often occurring area.

Besides the eastward MJO variance, the ratio between the variance of the eastward MJO and that of its westward counterpart (i.e., the westward wavenumber 1–6, 30–70-day mode) is also an important index to examine the model performance in MJO propagation. Figure 8 shows the ratio between the eastward and westward variance averaged over an Indian Ocean box within 5°N–5°S, 70°–100°E (Fig. 8a) and a western Pacific box within 5°N–5°S, 140°–170°E (Fig. 8b). Over the Indian Ocean (Fig. 8a), the eastward MJO variance roughly triples the westward variance in observations (the same as the CMIP3 models). The CMIP5 models generally produce a larger ratio than the CMIP3 models, with two of the 20 models (CNRM-CM5 and CSIRO) simulating a realistic or too large ratio, six other models (IPSL-5AL, IPSL-5AM, IPSL-5BL, MIROC5, MPI-E-L, MRI3, and NorE1-M) generating a ratio larger than two, and no model producing a ratio smaller than one (i.e., westward variance dominates over eastward variance). In the western Pacific (Fig. 8b), many models generally perform poorly over the western Pacific with the ratio less than one, which may be because of the double-ITCZ problem in many of the models or an inability to simulate the propagation from the Indian Ocean to the western Pacific. Only two models (CNRM-CM5 and FGOALS) produce a nearly realistic ratio, while seven models generate a ratio smaller than one.

Lag correlations between each longitude and a given longitude have been recommended to reveal zonal propagation by the MJO Working Group (Waliser et al. 2009) and used in various studies (e.g., Lin et al. 2006; Kim et al. 2011b; Weaver et al. 2011). Figure 9 shows the lag autocorrelation of the 30–70-day precipitation anomaly averaged between 5°N and 5°S at 0°, 85°E. Both observational datasets show a prominent MJO eastward-propagating footprint, with a phase speed of about 7 m s⁻¹. The models display a wide range of propagation characteristics that are consistent with the results shown in Fig. 8a. The two models with a realistic or too large ratio (CNRM-CM5 and CSIRO) show a highly coherent eastward-propagating signal. The phase speed is slightly slower than observations in CNRM-CM5 but much slower than observations in CSIRO. The seven models (IPSL-5AL, IPSL-5AM, IPSL-5BL, MIROC5, MPI-E-L, MRI3, and NorE1-M) with the eastward/westward ratio in the Indian Ocean being larger than 2 but smaller than in observations show only discernible eastward-propagating signals, however with slower phase speeds than observed. Other models with the ratio nearly equal to 1 show standing oscillations. The results are poor when using a western Pacific reference point (not shown), which is consistent with the worse eastward/westward ratio in Fig. 8b.

Figure 10 shows the power spectrum analysis with normalized spectra of the eastward wavenumber 1–6 component at 0°, 85°E. Both of the observational datasets show prominent spectral peaks between 30- and 70-day periods, with the power of 1DD lower than that of GPI. CNRM-CM5, IPSL-5AL, IPSL-5BL, CSIRO, and MIROC5 produce the period in the 30–70-day spectral peak of the MJO. However, the period of MJO in four of the above five CMIP5 models is between 45 and 70 days, which is longer than in observations. The only model showing a nearly correct MJO period is IPSL-5BL. Nevertheless, except for CNRM model, all
Fig. 5. As in Fig. 4, but for the 15°N–15°S antisymmetric component of precipitation.
Fig. 5. (Continued)
of these models do not produce correct propagation, as shown in Fig. 9. Moreover, the normalized spectra of the models are overreddened with too much variance at the low-frequency end, suggesting the model precipitation is more persistent than observation. We will return to this point in the next subsection.

e. Autocorrelation of precipitation

The autocorrelation analysis is similar to that in Lin et al. (2006). For the first-order Markov process [Eq. (1) in Lin et al. 2006], the redness of the spectrum is determined by its lag-1 autocorrelation $\rho$ [Eq. (2) in Lin
et al. 2006]. Therefore, we plot in Fig. 11 the auto-
correlation function of precipitation at 0°, 85°E. Both
observational datasets have a \( \rho \) of about 0.7. The CMIP5
models generally produce a smaller value of \( \rho \) than CMIP3
models. Three of the 20 CMIP5 models (MIROC4H,
MIROC-E, and MIROC-EC) have a \( \rho \) similar to or
smaller than the observed value. Moreover, the au-
tocorrelation values at longer time lags are generally
smaller and more realistic in the CMIP5 models than
in the CMIP3 models, which is consistent with the
better MJO spectral peaks in the CMIP5 models.
Nevertheless, all the CMIP5 models analyzed in this
study have too large values of \( \rho \) at the lag beyond 5
days, suggesting that they have too strong persistence
of precipitation, which is closely associated with their
overreddened spectra. This may contribute to the too
long MJO period (50–90 days) and slow MJO phase
speed in those models compared to observations (Figs.
9 and 10). In addition to the shape of the spectrum, the
precipitation persistence also affects the modes at the
high-frequency end of the spectrum, such as the WIG
mode (the 2-day wave). Since strong persistence means
that the precipitation anomaly keeps its sign for a long
time and does not oscillate, a too strong persistence
tends to suppress the high-frequency modes and may
contribute too weak variances of these modes in the
models (Fig. 6e).

f. CMIP5 versus CMIP3

To examine the differences between CMIP3 and
CMIP5 models in terms of their tropical intraseasonal
variability in more detail, we compare the simulation of
the mean state and variances of the MJO and CCEWs
for eight models that are both available for CMIP3 and
CMIP5. Figure 12 shows the scatterplots of CMIP5
versus CMIP3 for annual mean precipitation and vari-
cances of individual modes. The plotted values are the
average over 15°N–15°S, 65°–185°E. There exists a wide
range of uncertainty in the annual mean precipitation
rate, with the 1DD observation (~5.3 mm day\(^{-1}\)) being

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**FIG. 6.** Variances of (a) Kelvin, (b) ER, (c) MRG, (d) EIG, and (e) WIG modes along the equator averaged between
15°N and 15°S.
much smaller than the GPI observation (~6.3 mm day⁻¹; Fig. 12a). Six of the eight models (CCSM4, CNRM-CM, IPSL, MIROC-L, MIROC-H, and MRI) produce larger annual mean precipitation in CMIP5 than in CMIP3 (Fig. 12a). The mean precipitation rate in all models is larger than that from 1DD and is closer to the GPI observation except for the CSIRO-Mk3 CMIP3 simulation, which is slightly smaller than the 1DD observation.

Except for MPI, the MJO variance in CMIP5 is stronger than or comparable to that from CMIP3 (Fig. 12b). Although all eight models show smaller variance than observations for the Kelvin waves (Fig. 12c), three of them (CCSM4, CNRM-CM, and MRI) produce better simulations in CMIP5 than in CMIP3. For ER (Fig. 12d), CMIP5 and CMIP3 simulations are comparable except for CCSM4, which produces much larger variance in CMIP5 than in CMIP3 and observations. However, two CMIP5 models (CCSM4 and CNRM-CM) show marked progress, while some models have better ER variance in CMIP3 than in CMIP5. Consistent with the result shown in Fig. 6c, the MRG variance in all of eight models is too weak when compared to observations (Fig. 12e), with no clear overall improvements among models from CMIP3 to CMIP5. For the EIG variance (Fig. 12f), most models show larger values in their new CMIP5 version, and four models (CCSM4, CNRM-CM, CSIRO-Mk3, and MIROC-H) have their values between GPI and 1DD observed values. For WIG (Fig. 12g), similar to the MRG, all of the models show too weak a value compared to the observations with no clear overall improvement from CMIP3 to CMIP5. Two models (CCSM4 and CNRM-CM) show improved EIG in CMIP5 compared with CMIP3, while three models (MIROC-L, MIROC-H, and MPI) have better simulations in CMIP3 than CMIP5.

Overall, among the eight models we have examined, many produce larger annual mean precipitation over the Indo-Pacific warm pool in CMIP5 than in CMIP3. Several models (e.g., CCSM4, CNRM-CM, and MRI) show more improvement in many wave modes in CMIP5 than in CMIP3. Additional discussion is provided in the next section.

5. Summary and discussion

This study evaluates the tropical intraseasonal variability, especially the MJO and CCEWs, simulated by 20 CMIP5 coupled GCMs. The results are compared with the simulations of 14 CMIP3 models evaluated by Lin et al. (2006) and show that the CMIP5 models have an overall improvement over the CMIP3 models in the simulation of tropical intraseasonal variability, especially the MJO and several CCEWs. The CMIP5 models generally produce larger total intraseasonal (2–128 day) variance of precipitation when compared to the CMIP3 models, as well as larger variances of Kelvin, ER, and EIG waves. About half of the models have signals of convectively coupled equatorial waves, with Kelvin and MRG-EIG waves especially prominent, and the phase speeds are generally realistic, being scaled to correct equivalent depths, which suggests that these models are producing large enough reduction in their effective static stability by diabatic heating.

The CMIP5 models generally produce larger MJO variance than the CMIP3 models over the Indo-Pacific region (about 25% average increase), and a more realistic ratio between the eastward MJO variance and the variance of its westward counterpart. About one-third of the CMIP5 models generate the spectral peak of MJO precipitation between 30 and 70 days. However, the phase speeds of the model MJO tend to be too slow and the period is longer than observations as part of an
overreddened spectrum, which in turn is associated with too strong persistence of equatorial precipitation.

For CMIP5, several modeling centers provided a series of models with varying complexity and spatial resolutions ranging from atmosphere–ocean general circulation models (AOGCMs), to more comprehensive Earth system models (ESMs), including some that are coupled to chemical models. They are usually using the same atmospheric model but sometimes with different resolutions. Among the 20 models we analyzed, we have four such groups that provide “standard models” (i.e., AOGCMs) as well as ESMs: 1) CanCM4 and CanESM2; 2) IPSL-CM5A-LR and IPSL-CM5A-MR; 3) MIROC5, MIROC-E, and MIROC-EC; and 4) HadCM3, Had-G2-CC, and Had-G2-ES. Within each group, the skill of simulating the MJO or convectively coupled equatorial waves is similar, suggesting that the simulated tropical intraseasonal variability is not sensitive to model resolution or chemical processes.

Our results demonstrate that the too strong persistence of precipitation in many CMIP3 models has been reduced in the CMIP5 models, which may contribute to
FIG. 9. Lag correlation of the 30–70-day precipitation anomaly averaged along the equator between 5°N and 5°S with respect to itself at 0°, 85°E. The three diagonal lines correspond to phase speeds of 3, 7, and 15 m s⁻¹, respectively.
the improved tropical intraseasonal variability in some models. However, the persistence of precipitation in many CMIP5 models is still larger than observations (Fig. 11), which is also reflected by the too red precipitation (Fig. 10) and space–time spectra (Fig. 3). The weak persistence of precipitation in observations may be associated with the well-known self-suppression processes in deep convection, with convective downdrafts reducing...
the entropy of the boundary layer and the mesoscale downdrafts reducing the entropy of the lower troposphere, and diluted convective updrafts being sensitive to the change of boundary layer and lower troposphere entropy [see more detailed discussion in Lin et al. (2006) and references therein]. The current GCMs have not included all the above self-suppression processes in deep convection, especially the diluted convective updrafts, convective downdrafts, and mesoscale downdrafts. Better representation of these physical processes may help to further improve the simulation of tropical intra-seasonal variability.

Many CMIP5 models are able to simulate much larger MJO variance than the CMIP3 models and can even produce the 30–70-day spectral peak of MJO. These are notable improvements in MJO modeling. Models generating large MJO variance and the 30–70-day spectral peak (e.g., CNRM-CM5, CSIRO, IPSL-5BL, and MIROC5) have different types of convective closure (Table 1), suggesting that better simulations of MJO variance and spectral peak are not linked to a specific type of convective closure. However, the eastward propagation of MJO is still difficult to reproduce. The only model that can produce a realistic eastward propagation of MJO (CNRM-CM5) is the only model using a moisture-convergence-type closure for convection, suggesting that the low-level moisture convergence may play an important role in the MJO’s eastward propagation.

Several models (e.g., CCSM4, CNRM-CM5, and MRI) show improvement in many wave modes in CMIP5 as
compared with CMIP3. It would be very interesting to study what led to the improvements, which may be beneficial for future model development. This is beyond the scope of the current study. We have tried to diagnose some physical relationships related to tropical intraseasonal variability; however, some key variables are not available yet in the public domain, especially for the daily outputs necessary for studying intraseasonal variability. Therefore, we can only provide some discussion based on the available model documents. For CCSM4, as demonstrated by Zhou et al. (2012), the significant improvement of MJO simulation can be attributed to two modifications to the deep convection scheme: a dilute plume approximation and an implementation of convective momentum transport (CMT). The dilute plume approximation makes the temperature and convective heating anomalies more positively correlated to generate more available potential energy for the MJO. The inclusion of CMT leads to a better simulation of low-level zonal winds and a better propagation of MJO. For MRI, as shown by Yukimoto et al. (2012), a new convection scheme was installed that is a revision of the Tiedtke (1989) scheme with Nordeng (1994) modification, and also includes CMT. A new cloud scheme was also implemented that is an expansion of the Tiedtke (1993) cloud scheme. These make the model physics of the
MRI model closer to that of the MPI model. The latter has been shown to produce reasonable tropical intraseasonal variability in both CMIP3 and CMIP5, which has been hypothetically connected to its moisture-convergence-type convective closure/trigger (Lin et al. 2006). The CNRM model has been one of the best models in CMIP3 and CMIP5 in terms of tropical intraseasonal variability, which has also been hypothetically connected to its moisture-convergence-type convective closure/trigger (Lin et al. 2006). As documented by Voldoire et al. (2013), the main improvements from the CMIP3 version to the CMIP5 version are higher resolution, a new dynamical core, a new radiation scheme, and better conservation of mass and water in the atmosphere. The deep convection scheme remains the same as the CMIP3 version. Therefore, the better simulation of tropical intraseasonal variability in CMIP5 is connected to the above model improvements. This does not necessarily exclude the possible effect of convection scheme since sometimes the performance of a convection scheme is resolution dependent (Inness et al. 2001). Overall, the improved tropical intraseasonal variability in these three models suggests the possible importance of diluted convective updrafts, CMT, and a moisture-convergence-type convective closure/trigger.
FIG. 12. Scatterplots of CMIP5 value vs CMIP3 value for (a) annual mean precipitation, and the variances of (b) MJO, (c) Kelvin, (d) ER, (e) MRG, (f) EIG, and (g) WIG modes. All values are averaged over the region 15°N–15°S, 65°–185°E.
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