North American Monsoon and Convectively Coupled Equatorial Waves Simulated by IPCC AR4 Coupled GCMs

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ABSTRACT

This study evaluates the fidelity of North American monsoon and associated intraseasonal variability in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) coupled general circulation models (CGCMs). Twenty years of monthly precipitation data from each of the 22 models' twentieth-century climate simulations, together with the available daily precipitation data from 12 of them, are analyzed and compared with Global Precipitation Climatology Project (GPCP) monthly and daily precipitation. The authors focus on the seasonal cycle and horizontal pattern of monsoon precipitation in conjunction with the two dominant convectively coupled equatorial wave modes: the eastward-propagating Madden-Julian oscillation (MJO) and the westward-propagating easterly waves.

The results show that the IPCC AR4 CGCMs have significant problems and display a wide range of skill in simulating the North American monsoon and associated intraseasonal variability. Most of the models reproduce the monsoon rainbelt, extending from southeast to northwest, and its gradual northward shift in early summer, but overestimate the precipitation over the core monsoon region throughout the seasonal cycle and fail to reproduce the monsoon retreat in the fall. Additionally, most models simulate good westward propagation of the easterly waves, but relatively poor eastward propagation of the MJO and overly weak variances for both the easterly waves and the MJO. There is a tendency for models without undiluted updrafts in their deep convection scheme to produce better MJO propagation.

1. Introduction

The North American monsoon, also known as the southwest U.S. monsoon, the Mexican monsoon, or the Arizona monsoon, significantly affects the precipitation

and large-scale circulation over much of the western United States and northwestern Mexico (Douglas et al. 1993; Higgins et al. 1997; Adams and Comrie 1997; Barlow et al. 1998; Higgins and Shi 2001; see schematic in Fig. 1) and has stimulated strong interest in the prediction and research communities, leading to the recent North American Monsoon Experiment (NAME; Higgins and NAME Science Working Group 2003; Higgins et al. 2006; Vera et al. 2006). The North American monsoon also has strong intraseasonal variability with two

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FIG. 1. Schematic depiction of the North American monsoon and its two dominant convectively coupled equatorial wave modes: MJO and easterly waves. Contour denotes the percentage of annual mean GPCP precipitation that falls in the monsoon season (July–September). The two boxes denote the regions with the largest seasonal variation, with the northern box being the core monsoon region.

dominant modes: the Madden–Julian oscillation (MJO) that propagates eastward from the western and central Pacific (Higgins and Shi 2001; Lorenz and Hartmann 2006) and easterly waves that propagate westward from the Atlantic Ocean (e.g., Lau and Lau 1990; Avila 1991; Avila and Pasch 1992; Molinari et al. 1997; Raymond et al. 1998; Zehnder et al. 1999; Molinari et al. 2000; Fuller and Stensrud 2000; Serra and Houze 2002; Petersen et al. 2003; Adams and Stensrud 2007). Both of these modes significantly modulate the monsoon precipitation and the formation, intensity, and track of the tropical cyclones and are therefore important for both weather and climate prediction.

Many previous studies have used high-resolution regional models to simulate the North American monsoon and associated intraseasonal variability, and there have been significant improvements from the earlier simulations to more recent studies (e.g., Giorgi 1991; Dunn and Horel 1994; Anderson et al. 2000; Gochis et al. 2002; Mo and Juang 2003). Currently there is a comprehensive multimodel assessment project associated with NAME (Gutzler et al. 2005). For the general circulation models (GCMs), on the other hand, only a few previous studies have examined the simulations of the North American monsoon and associated intraseasonal variability by *individual* models (e.g., Krishnamurti et al. 2000; Arritt et al. 2000; Yang et al. 2001; Berbery and Fox-Rabinovitz 2003; Kunkel 2003; Farrara and Yu 2003; Collier and Zhang 2006; Lee et al. 2007). The success of these simulations is sensitive to a variety of factors, such as horizontal resolution (Berbery and Fox-

Rabinovitz 2003; Lee et al. 2007), boundary conditions (Yang et al. 2001), and convective parameterization (Collier and Zhang 2006). However, to our knowledge, no multimodel intercomparison has been conducted to evaluate the general status of the simulations of the North American monsoon and associated intraseasonal variability in the GCMs.

Recently, in preparation for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), more than 20 international climate modeling centers conducted a comprehensive set of long-term simulations both for twentieth-century climate and for different climate change scenarios in the twenty-first century. Before conducting the extended simulations, many of the modeling centers updated their physical schemes to incorporate recent research results. Many model intercomparison studies have evaluated the dominant tropical modes simulated by the IPCC AR4 coupled general circulation models (CGCMs), such as the annual mean ITCZ (Lin 2007), ENSO (AchutaRao and Sperber 2006; Capotondi et al. 2006; Joseph and Nigam 2006), the MJO, and convectively coupled equatorial waves (Lin et al. 2006). For example, Lin et al. (2006) evaluated the all-season behavior of the MJO and convectively coupled equatorial waves in 14 models. They found that about half of the models have signals of convectively coupled equatorial waves, with especially prominent Kelvin and mixed Rossby–gravity (MRG)–eastward inertio-gravity (EIG) waves. However, the variances are generally too weak for all wave modes except the EIG wave, and the phase

speeds are generally too fast, being scaled to excessively deep equivalent depths, which suggests that these models may not have a large enough reduction in their “effective static stability” by diabatic heating. The MJO variance approaches the observed value in only 2 of the 14 models, but is less than half of the observed value in the other 12 models. The ratio between the eastward MJO variance and the variance of its westward counterpart is too small in most of the models, which is consistent with the lack of highly coherent eastward propagation of the MJO in many models. Moreover, the MJO variance in 13 of the 14 models does not come from a pronounced spectral peak; rather, it usually comes from part of an overreddened spectrum, which in turn is associated with too-strong persistence of equatorial precipitation. The two models that arguably do best at simulating the MJO are the only ones with convective closures/triggers linked in some way to moisture convergence.

The purpose of this study is to extend the Lin et al. (2006) study to evaluate the North American monsoon and associated intraseasonal variability in the IPCC models. The questions we address are as follows:

- 1) How well do the models simulate the North American monsoon?
- 2) How well do the models simulate the intraseasonal precipitation signals associated with the North American monsoon, especially the MJO and tropical easterly waves?
- 3) Is there any systematic dependence of model simulations on the basic characteristics of convection schemes, such as their cloud models or closure assumptions?

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

This analysis is based on 21 yr (model years 1979–99) of simulations of the climate of the twentieth century (20C3M) from 22 IPCC AR4 CGCMs. Table 1 lists the model names and acronyms, their horizontal and vertical resolutions, and brief descriptions of their deep convection schemes. Models with the same or similar deep convection schemes are listed together in Table 1 and in all the figures in this paper. For each model we use 20 yr of monthly mean surface precipitation. In addition, daily precipitation is available for 12 of the models, and we use 8 yr of daily data from each model to study the intraseasonal variability.

The model simulations are validated using the Global Precipitation Climatology Project (GPCP) version 2 precipitation data (Adler et al. 2003; Huffman et al. 2001). We use 21 yr (1979–99) of monthly data with a horizontal resolution of 2.5° longitude by 2.5° latitude, and 8 yr (1997–2004) of daily data with a horizontal resolution of 1° longitude by 1° latitude.

It is important to note that currently there are still large uncertainties associated with global precipitation analyses such as the GPCP dataset used in this study. The uncertainties come from many different sources, especially the lack of in situ measurement in certain geographical regions. Many efforts are being taken to reduce these uncertainties, especially with the aid of the extensive measurements from recent field experiments such as NAME and the East Pacific Investigation of Climate (EPIC).

3. Method

The MJO is defined as significant rainfall variability in eastward zonal wavenumbers 1–6 and in the period range of 24–70 days. It is isolated using the following procedure. (i) The 8 yr (2922 days) of daily precipitation data were averaged along the latitude belt between 5° and 25°N , where the eastward propagation of MJO mainly occurs during northern summer. We analyzed the intraseasonal variance of the entire latitude circle. All data were first linearly interpolated to a fine zonal resolution of 1° longitude, and then averaged over each 10° grid box. (ii) The space–time spectrum was calculated using a discrete Fourier transform for the whole 8-yr time series. (iii) We then used an inverse space–time Fourier transform to get the time series of the eastward component for wavenumbers 1–6, which includes all available frequencies. (iv) These time series were filtered using a 365-point 24–70-day Lanczos filter (Duchon 1979), whose response function was shown in Lin et al. (2006). Because the Lanczos filter is nonrecursive, 182 days of data were lost at each end of the original time series (days 1–182 and 2741–2922), so the length of the time series became 2558 days. (v) The resultant eastward wavenumber 1–6, 24–70-day anomaly during northern summer (May–October) is hereafter referred to as the MJO anomaly. (vi) Its variance was also compared with the variance of its westward counterpart (i.e., the westward wavenumber 1–6, 24–70-day anomaly), which was isolated using the same method as above.

The procedure for isolating the westward-propagating easterly waves is also same as above except for the westward wavenumber 6 and up, 3–6-day mode (Kila-

TABLE 1. List of models that participate in this study.

Modeling groups	IPCC ID (label in figures)	Grid type, resolution, model top	Deep convection scheme/modification	Downdrafts* SC/UC/Meso	Closure/trigger	Flux correction
National Center for Atmospheric Research	CCSM3 (CCSM3)	Spectral, T85×L26, 2.2 mb	Zhang and McFarlane (1995)	Yes/no/no	CAPE	No
National Center for Atmospheric Research	PCM (PCM)	Spectral, T42×L26, 2.2 mb	Zhang and McFarlane (1995)	Yes/no/no	CAPE	No
Canadian Centre for Climate Modeling and Analysis	CGCM3.1-T47 (CGCM-T47)	Spectral, T47×L32, 1 mb	Zhang and McFarlane (1995)	Yes/no/no	CAPE	Heat, water
Canadian Centre for Climate Modeling and Analysis	CGCM3.1-T63 (CGCM-T63)	Spectral, T63×L32, 1 mb	Zhang and McFarlane (1995)	Yes/no/no	CAPE	Heat, water
Los Alamos Study Group/Institute of Atmospheric Physics	Flexible Global Ocean–Atmosphere–Land System Model gridpoint version 1.0 FGOALS-g1.0 (IAP)	Grid point, 64×32×L32, 2 mb	Zhang and McFarlane (1995)	Yes/no/no	CAPE	No
NASA Goddard Institute for Space Studies	GISS-AOM (GISS-AOM)	Grid point, 90×60×L12	Russell et al. (1995)	No/no/no	CAPE	No
NASA Goddard Institute for Space Studies	GISS-ER (GISS-ER)	Grid point, 72×46×L20, 0.1 mb	Del Genio and Yao (1993)	Yes/no/no	Cloud-base buoyancy	No
NASA Goddard Institute for Space Studies	GISS Model E-H (GISS-EH)	Grid point, 7×46×L20, 0.1 mb	Del Genio and Yao (1993)	Yes/no/no	Cloud-base buoyancy	No
Hadley Centre for Climate Prediction and Research/Met Office	Met Office HadCM3 (HadCM3)	Spectral, T63×L18, 4 mb	Gregory and Rowntree (1990)	Yes/no/no	Cloud-base buoyancy	No
Hadley Centre for Climate Prediction and Research/Met Office	Met Office HadGEM1 (HadGEM1)	Spectral, T63×L18, 4 mb	Gregory and Rowntree (1990)	Yes/no/no	Cloud-base buoyancy	No
CSIRO Atmospheric Research	CSIRO Mk3.0 (CSIRO)	Spectral, T63×L18, 4 mb	Gregory and Rowntree (1990)	Yes/no/no	Cloud-base buoyancy	No
Meteorological Research Institute	MRI-CGCM2.3.2 (MRI)	Spectral, T42×L30, 0.4 mb	Pan and Randall (1998)	Yes/no/no	CAPE	Heat, water

TABLE 1. (Continued)

Modeling groups	IPCC ID (label in figures)	Grid type, resolution, model top	Deep convection scheme/modification	Downdrafts* SC/UC/Meso	Closure/trigger	Flux correction
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change	MIROC3.2-high-resolution version (MIROC-hires)	Spectral, T106×L56	Pan and Randall (1998); Emori et al. (2001)	Yes/no/no	CAPE/relative humidity	No
Same as above	MIROC3.2-medres (MIROC-medres)	Spectral, T42×L20, 30 km	Pan and Randall (1998); Emori et al. (2001)	Yes/no/no	CAPE/relative humidity	No
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0 (GFDL2.0)	Grid point, 144×90×L24, 3 mb	Moorthi and Suarez (1992); Tokioka et al. (1988)	No/no/no	CAPE/threshold	No
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1 (GFDL2.1)	Grid point, 144×90×L24, 3 mb	Moorthi and Suarez (1992); Tokioka et al. (1988)	No/no/no	CAPE/threshold	No
Max Planck Institute for Meteorology	ECHAM5/MPI-OM (MPI)	Spectral, T63×L31, 10 mb	Tiedtke (1989); Nordeng (1994)	Yes/no/no	CAPE, moisture convergence	No
Meteorological Institute, University of Bonn;	ECHO-G (ECHO-G)	Spectral, T30×L19, 10 mb	Tiedtke (1989); Nordeng (1994)	Yes/no/no	CAPE/moisture convergence	Heat, water
Météo-France/Centre National de Recherches Météorologiques	CNRM-CM3 (CNRM)	Spectral, T63×L45, 0.05 mb	Bougeault (1985)	No/no/no	Kuo	No
Bjerknes Centre for Climate Research	BCCR-BCM2.0 (BCCR)	Spectral, T63×L31, 10 mb	Bougeault (1985)	No/no/no	Kuo	No
Institute for Numerical Mathematics (INM)	INM-CM3.0 (INM)	Grid point, 72×45×L21	Betts (1986)	No/no/no	CAPE	Water
Institute Pierre Simon Laplace (IPSL)	IPSL-CM4 (IPSL)	Grid point, 96×72×L19	Emanuel (1991)	Yes/yes/no	CAPE	No

* For downdrafts, SC: saturated convective downdrafts, UC: unsaturated convective downdrafts, and Meso: mesoscale downdrafts.

FIG. 2. Seasonal variation of precipitation averaged over (a) the core region of North American monsoon between 20° – 32.5° N and 100° – 115° W, and (b) the eastern Pacific warm pool region between 10° – 20° N and 100° – 115° W.

dis et al. 2006). This filter is close to the tropical depression (TD) band isolated in Wheeler and Kiladis (1999) and used in the Kiladis et al. (2006) study of African easterly waves. The methodology effectively excludes most variability associated with other westward waves, the 6-day cutoff eliminates equatorial Rossby waves, the 3-day cutoff eliminates westward in-

ertio-gravity (WIG) waves, and the westward wave-number 6 cutoff eliminates MRG waves. After the space-time filtering, the variance of the easterly waves was also compared with the variance of its eastward-propagating counterpart (i.e., the eastward wavenumber 6 and up, 3–6-day anomaly), which was isolated using the same method as above.

4. Results

a. Seasonal variation of precipitation

Figure 2a shows the seasonal cycle of precipitation averaged over the core region of the North American monsoon between 20° – 32.5° N and 100° – 115° W for observations and 22 IPCC AR4 CGCMs. Figure 2a demonstrates three points. First, the models display a large scatter in precipitation amplitude, with most of the models producing excessive precipitation throughout the entire seasonal cycle. Second, in observations the monsoon onset is in July, but the models display a wide range of onset time, with many models having a June onset [e.g., the Parallel Climate Model (PCM), the Bjerknes Centre for Climate Research model (BCCR), and the Community Climate System Model, version 3 (CCSM3)]. Third, in observations the monsoon ends in October, but many models keep the high monsoon precipitation until the end of the year [e.g., the Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3 (CNRM-CM3), PCM, the Goddard Institute for Space Studies Model E-R (GISS-ER), BCCR, and CCSM3].

Figure 2b is the same as Fig. 2a but for the eastern Pacific warm pool region between 10° – 20° N and 100° – 115° W. In contrast to the excessive precipitation over the core region of the North American monsoon, many models produce insufficient precipitation over the eastern Pacific warm pool. The observed monsoon onset time is June in this region, which is reproduced by many models. However, the observed ending of the monsoon in October is not well reproduced by many models, which tend to keep high precipitation until the end of the year.

To examine the northward/southward shift of monsoon precipitation, Fig. 3 shows the seasonal cycle of precipitation along the longitude belt between 100° and 115° W. In observations (Fig. 3a, repeated in Fig. 3m), the precipitation displays a gradual northward shift from March to July and a gradual southward shift from August to November. The model simulations show two characteristics. First, although many models can reproduce the gradual northward shift [e.g., CGCM-T47, the Institute of Atmospheric Physics (IAP) model, the Goddard Institute for Space Studies Atmosphere–Ocean Model (GISS-AOM), the Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3), the Geophysical Fluid Dynamics Laboratory Climate Model, version 2.0 (GFDL CM2.0), and the Max Planck Institute Ocean Model (MPI-OM)], there are quite a few models which produce a (nearly) simultaneous increase of precipitation in northern and southern latitudes in early summer (e.g., PCM, GISS-ER,

GFDL CM2.1, CNRM-CM3, and BCCR), corresponding to the too-early monsoon onset in those models over the core region of the North American monsoon (Fig. 2a). Second, most of the models fail to reproduce the gradual southward shift of precipitation from August to November and keep high precipitation in the northern latitudes until the end of the year. There is no obvious correspondence between models that fail to reproduce the monsoon retreat and those simulating a too-early monsoon onset.

Next we look at the horizontal pattern of precipitation in July when the monsoon is at its peak (Fig. 4). The observed precipitation (Fig. 4a, repeated in Fig. 4m) displays a rainbelt extending from southeast to northwest. Most of the models produce the rainbelt, suggesting that the models can capture the basic mechanism for the formation of the North American monsoon, although the magnitude is often too large. In addition, in several models the simulated rainbelt is isolated from the precipitation over the eastern Pacific warm pool, which is different from observations [e.g., the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mark, version 3.0 (Mk3.0), and the Model for Interdisciplinary Research on Climate, medium-resolution version (MIROC-medres)].

b. The MJO

Now we focus on the variance of the MJO, that is, the daily variance of the eastward wavenumber 1–6, 24–70-day mode. Figure 5 shows that the MJO variance along the equator averaged between 5° and 25° N. In observations, MJO variance has its maximum over the eastern Pacific warm pool. The model variance approaches the observed value in only one model (ECHAM5/MPI-OM), but is less than half of the observed value in all other 11 models. This is similar to the performance of these models in simulating the all-season MJO over the Indian Ocean and western Pacific, for which the simulated variance is less than half of the observed value in 10 of the 12 models (Lin et al. 2006).

In addition to the variance, another important index for evaluating the MJO simulation is the ratio between the variance of the eastward MJO and that of its westward counterpart (i.e., the westward wavenumber 1–6, 24–70-day mode), which is important for the zonal propagation of tropical intraseasonal oscillation. Figure 6 shows the ratio between the eastward variance and the westward variance averaged over an eastern Pacific box between 5° – 25° N and 100° – 140° W. In the observation, the eastward MJO variance is double that of the westward variance. The 12 models may be divided into two groups. Seven models simulate a ratio larger than or close to one [CSIRO Mk3.0, the Meteo-

FIG. 3. Seasonal variation of precipitation averaged between 100° and 115° W for the observations and 22 models.

rological Research Institute (MRI) CGCM, MIROC-medres, GFDL CM2.0 and GFDL CM2.1, MPI-OM, and CNRM-CM3], and the others simulate a ratio much less than one (i.e., westward variance dominates

over eastward variance). Interestingly, the models in the second group all have undiluted updrafts in their deep convection scheme, while none of those in the first group have undiluted updrafts. This suggests that re-

FIG. 3. (Continued)

moving undiluted updrafts may help improve the propagation of the MJO in GCMs.

The competition between the eastward MJO variance and its westward counterpart largely determines the zonal propagation characteristics of the tropical in-

traseasonal oscillation. When the ratio is much more (less) than one, most of the tropical intraseasonal oscillation events will propagate eastward (westward). A useful method for evaluating the MJO simulation is to look at the propagation of the 24–70-day filtered

FIG. 4. July mean precipitation for the observations (GPCP) and 22 models.

anomaly of the raw precipitation data, which includes all wavenumbers, to see if the MJO mode (the eastward wavenumber 1–6 mode) dominates over the other modes, as is the case in the observations. Because the tropical intraseasonal oscillation is dominated by zon-

ally asymmetric, planetary-scale phenomena, the competition is mainly between the MJO and its westward counterpart—the westward wavenumber 1–6 component. Figure 7 shows the lag correlation of the 24–70-day precipitation anomaly averaged between 5° and

FIG. 4. (Continued)

25°N with respect to itself at 10°N, 255°E. The observational data show prominent eastward-propagating signals of the MJO, with a phase speed of about 5 m s^{-1} . The models display a wide range of propagation characteristics that are consistent with the ratio be-

tween the eastward MJO variance and its westward counterpart shown in Fig. 6. The three models with a ratio larger than 1.5 (CSIRO Mk3.0, GFDL2.0, and GFDL2.1) show a discernable eastward-propagating signal, but other models with the eastward/

FIG. 5. Variance of the MJO averaged between 5° and 25°N for May–October.

westward ratio nearly equal to one or less than one show a standing oscillation (e.g., PCM and MRI CGCM) or westward propagation (e.g., GISS-AOM and GISS-ER).

In addition to the eastward-propagating component, the MJO also has a slow northward-propagating component, which takes the MJO signals from near the equator to the core North American monsoon region. Figure 8 shows the lag correlation of the 24–70-day precipitation anomaly along the latitude belt averaged between 100° and 115°W with respect to itself at 12°N, 107°W. The observational data show highly coherent northward-propagating signals of the MJO, with a phase speed of about 2.5 m s^{-1} . Eight of the 12 models simulate coherent northward propagation (PCM, CGCM, CSIRO Mk3.0, MRI CGCM, MIROC-medres, GFDL2.0, GFDL2.1 and MPI-OM) but sometimes with a too-fast phase speed. The other four models show a standing oscillation (CCSM3, CNRM-CM3) or even southward propagation (GISS-AOM, GISS-ER). There is no one-to-one correspondence between models with good northward propagation and those with good eastward propagation.

c. Easterly waves

Figure 9 shows the variance of easterly waves averaged between 10° and 20°N. Two of the 12 models (MPI-OM and CNRM-CM3) simulate nearly realistic variance of easterly waves, although the maximum is shifted slightly to the west for the MPI-OM. However, all other 10 models produce variance that is less than half of the observed value.

Figure 10 shows the ratio between the variance of the westward-propagating easterly waves and that of its eastward-propagating counterpart averaged over an

FIG. 6. Ratio between the variance of the MJO and the variance of its westward counterpart (westward wavenumber 1–6, 24–70-day mode). The variances are averaged over an eastern Pacific box between 5°–25°N and 100°–140°W for May–October.

eastern Pacific box between 10°–20°N and 70°–120°W. In the observation, the westward variance roughly doubles the eastward variance. All models simulate a ratio larger than one (i.e., westward variance dominates over eastward variance), and three of the models simulate an overly large ratio (MRI CGCM, MPI-OM, and CNRM-CM3). Consistently, most of the models display a highly coherent westward propagation of easterly waves (not shown).

5. Summary and discussion

This study evaluates the fidelity of North American monsoon and associated intraseasonal variability in IPCC AR4 CGCMs. Twenty years of monthly precipitation data from each of the 22 models' twentieth-century climate simulation, together with the available daily precipitation data from 12 of them, are analyzed and compared with GPCP monthly and daily precipitation data. We focus on the seasonal cycle and horizontal pattern of monsoon precipitation, together with the two dominant intraseasonal modes: the eastward-propagating MJO and the westward-propagating easterly waves.

The results show that the IPCC AR4 CGCMs have significant problems and display a wide range of skill in simulating the North American monsoon and associated intraseasonal variability. Most of the models reproduce the monsoon rainbelt extending from southeast to northwest and its gradual northward shift in early summer but overestimate the precipitation over the core monsoon region throughout the seasonal cycle

FIG. 7. Lag correlation of the 24–70-day precipitation anomaly averaged between 5° and 25°N with respect to itself at 15°N , 245°E . Shading denotes the regions where lag correlation is above the 95% confidence level. The three thick lines correspond to phase speeds of 3, 5, and 8 m s^{-1} , respectively.

and fail to reproduce the monsoon retreat in the fall. Most models simulate good westward propagation of the easterly waves but relatively poor eastward propagation of the MJO and overly weak variances for both

the easterly waves and the MJO. There is a tendency for models without undiluted updrafts in their deep convection scheme to produce better MJO propagation.

FIG. 7. (Continued)

The 22 models provide a large variety of model physics, such as all the major deep convection schemes with different types of convective closures, convective triggers, and cloud models (Table 1). Recall that models with the same or similar deep convection schemes are listed together in Table 1 and in all the figures in this paper. For the seasonal cycle and horizontal pattern of the North American monsoon, we do not find any systematic dependence of model simulations on the type of closure assumptions or cloud models. For the intraseasonal variability, however, the two models with the largest variances of easterly waves (MPI-OM and CNRM-CM3; Fig. 9) are the only models with their convective closure/trigger linked in some way to moisture convergence. The MPI-OM also produces the largest northern summer MJO variance in the North

American monsoon region (Fig. 5); additionally, these two models simulate the largest all-season MJO variances over the Indian Ocean and western Pacific (Lin et al. 2006). Therefore, the moisture convergence closure/trigger seems to be helpful for enhancing the variances of the MJO and easterly waves in GCMs. This is inconsistent with the results of Slingo et al. (1996), who found that for the Atmospheric Model Intercomparison Project (AMIP) models, deep convection schemes with CAPE-type closure tend to produce larger MJO signals than schemes with moisture convergence-type closure.

Another interesting finding of this study is that convection schemes without undiluted updrafts tend to produce better eastward propagation of the MJO. Removing undiluted updrafts may help to better represent the shallow convective clouds and associated premoist-

FIG. 8. Lag correlation of the 24–70-day precipitation anomaly averaged between 100° and 115° W with respect to itself at 12° N, 107° E. Shading denotes the regions where lag correlation is above the 95% confidence level. The three thick lines correspond to phase speeds of 1.2, 2.5, and 7.5 m s^{-1} , respectively.

FIG. 10. Ratio between the variance of the westward-propagating easterly waves and the variance of its eastward-propagating counterpart (eastward 3–6-day mode). The variances are averaged over 10°–20°N and 70°–120°W for May–October.

Many previous studies have shown that time mean precipitation is important for intraseasonal variability in GCMs (e.g., Inness and Slingo 2003; Sperber 2004). It is interesting, therefore, to compare the simulation of seasonal variation of precipitation and the simulation of subseasonal convectively coupled equatorial waves in the IPCC models. We want to address two questions. First, does larger seasonal mean precipitation in the models correspond to stronger intraseasonal variability? Our results give a negative answer. Although the MPI-OM does show both a large seasonal mean and strong intraseasonal variability, the PCM shows a large seasonal mean but a very weak intraseasonal variability (Figs. 2 and 5). Second, does good northward propagation of the MJO lead to better simulation of the seasonal northward shift of the rainbelt and monsoon onset in the core monsoon region? We did not find such a relationship in our results. The eight models simulating coherent northward MJO propagation (Fig. 8; PCM, CGCM, CSIRO Mk3.0, MRI CGCM, MIROC-medres, GFDL2.0, GFDL2.1, and MPI-OM) display different characteristics of the seasonally northward shift of the rainbelt (Fig. 3) from gradual propagation (e.g., CGCM-T47) to a sudden jump (e.g., PCM). Therefore, the simulation of seasonal variation and the simulation of intraseasonal variability seem to be different questions, which are possibly related to different model characteristics.

Moreover, the North American monsoon system is an open system and is strongly affected by the whole tropical mean climate. Previous studies have shown that significant biases in tropical mean climate, espe-

cially the well-known double-ITCZ problem, exist in the IPCC AR4 models (Lin 2007). Therefore, improving the simulation of the entire tropical mean climate may help to improve the simulation of the North American monsoon system.

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