Evaluating Diurnal Rainfall Signal Performance from CMIP5 to CMIP6

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ABSTRACT: This study provides a comprehensive overview of diurnal rainfall signal performance within the current collection of models in phase 6 of the Coupled Model Intercomparison Project (CMIP6). The results serve as a reference for understanding model physics performance to represent precipitating processes and atmosphere–land–ocean interactions in response to the diurnal solar radiation cycle. Performance metrics are based on the phase, amplitude, and two empirical orthogonal function (EOF) modes of the climatological diurnal rainfall cycle derived from a Tropical Rainfall Measuring Mission observational dataset. We found that the ensemble model biases of diurnal phase and amplitude over lands improved from CMIP5 to CMIP6; however, those over oceans are still highly uncertain among CMIP6 models. Evaluation with observed EOF modes shows that the CMIP6 models are bifurcated based on the second EOF (EOF2), which represents diurnal rainfall contrast of coastal regimes where large biases of phase and amplitude reside. While the model ensemble suggests that models benefit from higher resolution in simulating phase and amplitude biases, the most distinct difference between the bifurcations is that one group successfully captures prevailing nighttime rainfall over tropical islands and coasts, especially over the Maritime Continent. Convective rainfall diagnosed by cumulus parameterization is found to be responsible for such biases. Our results suggest that CMIP6 models have generally been improved in their representation of diurnal rainfall cycles; however, for coastal diurnal regimes, more study is needed to improve the model parameterization of precipitation processes interacting with islands and coastal regions as current model resolution is still too coarse to resolve them.

KEYWORDS: Rainfall; Climate models; Diurnal effects

1. Introduction

The prominent diurnal oscillation of the Earth system is a combined response of land, ocean, and atmosphere to the diurnal solar radiation cycle. However, the diurnal cycles of moist convection processes that manifest from these interactions also vary with topography, surface properties, and the climate systems in which they are embedded (Yang and Smith 2006; Kikuchi and Wang 2008; Johnson 2011). Diurnal convection cycles are also closely linked with the hydrological cycle and correlate with upward transport of heat and moisture in the tropics that is part of the global circulations (Slingo et al. 2003). In the context of climate model development, the diurnal cycle is a great test bed for evaluating moist physics representations of the interactions of each component in the model (Tapiador et al. 2019). Understanding the performance of the diurnal rainfall cycle can help clarify important physical processes and improve climate model capability to simulate precipitation processes and project future rainfall variability.

A more complete picture of diurnal rainfall regimes can be obtained using satellite data (Yang and Slingo 2001; Yang and Smith 2006; Kikuchi and Wang 2008; Tan et al. 2019). There are distinct diurnal rainfall features between land and oceans. On land, diurnal rainfall usually peaks during the afternoon, with 20%–40% of the mean rainfall value. In contrast, oceanic diurnal rainfall typically peaks at night, with 10%–20% of the mean rainfall. Diurnal rainfall signals can also be modulated by mesoscale convective activities, especially near coasts and orographic regions (Nesbitt and Zipser 2003). Coastal regions also have strong diurnal rainfall signals (Kikuchi and Wang 2008), as sea–land breezes modulate mesoscale convection over these regions (e.g., Mapes et al. 2003). Diurnal varying coastal convection can contribute to a large amount of mean rainfall and has been found to closely interact with coastal surface inhomogeneity and land topography (Yokoi et al. 2017; Qian 2008; Mapes et al. 2003). Examples of locations where this phenomenon occurs include over the Bay of Bengal (Slingo et al. 2003), the west coast of Colombia (Mapes et al. 2003), and the Maritime Continent (Mori et al. 2004). Over other complex topographical regions, such as the eastern leeward side of some topographical regions, mesoscale convective organizations often occur and propagate into adjacent plains (Carbone and Tuttle 2008; O and Kirstetter 2018). It is noteworthy that over the coastal region and topographical region, diurnal rainfall peak often occurs during late evening and into nighttime when low-level convergence occurs due to land–sea/mountain–valley breeze (Wang and Hsu 2019).

However, simulating diurnal signals remains challenging for many weather and climate models (Dai 2006; Lee et al. 2007; Covey et al. 2016; Tapiador et al. 2019). The diurnal rainfall

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cycle over the ocean is generally very weak (Dai and Trenberth 2004), while precipitating convection on land often starts too early and precipitation periods are extended too long (Dai and Trenberth 2004; Xie et al. 2002). These biases are often attributed to insufficient model resolution and physical schemes that are incapable of capturing precipitating processes (Tapiador et al. 2019). Owing to constraints of grid spacing ($\sim 10\text{--}100\text{ km}$; Schmidt et al. 2017), many processes crucial to diurnal rainfall, such as boundary layer interactions and mesoscale circulations with topography, are not resolved in climate models. Many models have shown improvements in diurnal rainfall cycle when model resolution is increased due to better resolution of diurnal coastal circulation variations (Ploshay and Lau 2010; Bacmeister et al. 2014), while some show explicit representation of convection is needed to improve diurnal rainfall representation (Dirmeyer et al. 2011). In addition to insufficient resolution, issues related to physical schemes that represent development of diurnal convection must still be addressed. For example, the early onset of convection can be attributed to the insufficient entrainment rate of cloud plumes (Stratton and Stirling 2012), lack of inhibition mechanism on convection initiation (Wang et al. 2015; Wang and Hsu 2019), and lack of cloud development life cycle in cumulus parameterization schemes (CPS) (Xie et al. 2002). The lack of propagation in diurnal rainfall can be attributed to tropospheric forcing on convective initiation of CPS (Xie and Zhang 2000), low-level moist environment effects on convective initiation (Takayabu and Kimoto 2008), and uplifting of low-level instability effects on convection (Han and Pan 2011; Lee et al. 2008; Wang et al. 2015). To further improve diurnal rainfall cycles in climate models, it is important to first understand current model performance in simulating diurnal rainfall.

Organized to prepare for the sixth IPCC assessment report, phase 6 of the Coupled Model Intercomparison Project (CMIP6) organizes experiments with specific scientific questions and provides a data hub for simulations from major climate models around the world. Models participating in CMIP6 include many improvements in model physics compared to models in previous phases such as CMIP5 and use finer spatial resolution (Eyering et al. 2016). Our study utilizes historical experiments in the current CMIP6 archive (<https://esgf-node.llnl.gov/search/cmip6/>) to evaluate model performance and document progress from CMIP5. Metrics used for diurnal rainfall performance in this study include diurnal phase (i.e., local time of diurnal rainfall peak), diurnal amplitude (i.e., difference between rainfall maximum and minimum), and empirical orthogonal function (EOF) modes.

In addition to commonly used metrics, we also used observed EOF modes of diurnal rainfall cycles for model evaluation. Diurnal rainfall cycles have been found to be well characterized using two EOF modes in Tropical Rainfall Measuring Mission (TRMM) data (Kikuchi and Wang 2008), and these EOF modes have been used in a model performance evaluation framework (Wang et al. 2011). However, EOF analysis comes with several caveats in evaluating model performance such as missing the observed variability modes if a model underestimates variability (Lee et al. 2019). To address possible issues with EOF, we also apply the common basis

function (CBF) method, which projects model simulations onto observed EOF modes. Therefore, the CBF method directly quantifies how well a model reproduces diurnal rainfall signals associated with the observed EOF, rather than indicating the internal variability of model simulations. Previous studies suggest that the CBF framework provides a more consistent framework for model intercomparison for many interannual and interdecadal modes than EOF (Lee et al. 2019). In this case, our results provide a more complete evaluation of future climate model development, especially for moist processes, and may help improve model capability to project rainfall variability under possible climate change scenarios.

The remainder of this paper is structured as follows. Section 2 introduces TRMM satellite observational data, CMIP6/CMIP5 models, and the model performance analysis framework. Section 3 summarizes the evaluation of root-mean-square error (RMSE) and correlations of diurnal phase and amplitude and provides a performance evaluation based on EOF analysis. Section 4 provides a discussion on possible moist physics improvements to better simulate diurnal rainfall regimes. Last, section 5 presents a summary of our findings and conclusions.

2. Methodology and data

a. Data

1) TRMM 3B42

For model evaluation, we use the TRMM 3B42 dataset, which consists of TRMM data merged with other satellite estimates (Simpson et al. 1996) from 1998 to 2009, to construct diurnal rainfall cycles. The data have a spatial resolution of 0.25° and cover $50^\circ\text{S}\text{--}50^\circ\text{N}$. This dataset is a combined product that includes various other satellite observations (Huffman et al. 2007) such as infrared, microwave, and radar datasets, and is scaled to match monthly mean rain gauge data. One noteworthy issue is the possible delay of rainfall detection in the infrared satellite observations that were merged into the TRMM 3B42 product. Kikuchi and Wang (2008) suggested that a 3-h delay due to residual cirrus should be considered when comparing with radar-based observations. Dai (2006) also reported delays when comparing infrared data with rainfall based on weather reports. However, we focus more on model uncertainties and pattern correlations of diurnal rainfall features, which are less affected by this time delay; therefore, we did not apply time shifting to correct for possible delays in the TRMM 3B42 dataset.

In the following analysis, we define the diurnal signal (RAVG) as the first diurnal harmonic (D) of the averaged diurnal cycle of the rainfall time series over local time i , expressed as

$$\text{RAVG}(i) = D(i) + R(i) = A \sin\left(\frac{2\pi i}{k}\right) + R(i), \quad i = 1, \dots, k, \quad (1)$$

where k depends on the rainfall cycle sampling frequency, and R is the residual of diurnal rainfall cycle. Diurnal amplitude is

TABLE 1. List of 12 CMIP5 coupled atmosphere–ocean climate models.

Model	Description	Spatial resolution	CPS references
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization, and Bureau of Meteorology (Australia)	192×145	Gregory and Rowntree (1990)
CCSM4	National Center for Atmospheric Research (United States)	288×192	Zhang and McFarlane (1995); Neale et al. (2008)
CMCC-CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy)	480×240	Nordeng (1994); Tiedtke (1989)
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (France)	256×128	Bougeault (1985)
EC-Earth	Irish Centre for High-End Computing (ICHEC), National University of Ireland (Ireland)	320×160	Tiedtke (1989); Bechtold et al. (2014)
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University (China)	128×60	Zhang and McFarlane (1995); Zhang and Mu (2005)
GFDL CM3	NOAA/Geophysical Fluid Dynamics Laboratory (United States)	144×90	Donner et al. (2001)
GISS-E2-H	NASA Goddard Institute for Space Studies (United States)	144×90	DelGenio et al. (2007)
INM-CM4	Institute for Numerical Mathematics (Russia)	180×120	Betts (1986)
IPSL-CM5A-MR	Institut Pierre-Simon Laplace (France)	144×143	Emanuel (1991)
MRI-ESM1	Meteorological Research Institute (Japan)	320×160	Yoshimura et al. (2015)
NorESM1-M	Norwegian Climate Centre (Norway)	144×96	Zhang and McFarlane (1995); Neale et al. (2008)

defined as the amplitude A of the sinusoidal signal. Diurnal peak phase is defined as the local hour of the sinusoidal signal peak. This method has been used in other diurnal cycle studies (Slingo et al. 2003; Yang and Smith 2006).

2) CMIP5/CMIP6 MODELS

Following CMIP5 (Taylor et al. 2012), CMIP6 (Eyring et al. 2016) is the most recent model intercomparison and provides a comprehensive archive of data for understanding the effects of future Earth system changes. One of the key questions the CMIP6 aims to answer is identifying “the origins and consequences of systematic model biases” (Eyring et al. 2016). In this study, we adopt 3-hourly datasets from the CMIP5 and CMIP6 archives to address systematic diurnal rainfall biases. The data of the historical simulations from 12 CMIP5 models and 12 CMIP6 climate models used in this study are summarized in Tables 1 and 2, respectively. A 35-yr series of 3-hourly rainfall dataset are from the CMIP5 (1971–2005) and CMIP6 (1980–2014) datasets under CMIP historical simulations with aerosol, greenhouse gas, and volcanic eruption forcing from 1850 to near present. The CMIP5 and CMIP6 models are interpolated onto the same grids, with a spatial resolution of 2.5° longitude $\times$ 2° latitude for fair comparison. All analyses shown below are averaged over whole year simulations. We found that the 35-yr dataset is enough for most models with a horizontal resolution of 1° and for EOF analysis in the tropics and subtropics. In addition to the total rainfall dataset, we also

analyze convective rainfall data from the CMIP archives to understand the effects of CPS, which is often blamed for diurnal rainfall biases in the climate models in previous CMIP phases (Dai 2006; Dai and Trenberth 2004).

b. Metrics of EOF/CBF analysis for diurnal cycle

The EOF is widely used to isolate prominent climate variability patterns from climate datasets (Wilks 2011). Although EOF mathematically searches for the orthogonal basis of the signals, it works well to identify the prominent diurnal harmonics modes in satellite data and models (Kikuchi and Wang 2008; Pritchard and Somerville 2009; Wang et al. 2011). Based on the observed EOF modes of diurnal rainfall cycles, Wang et al. (2011) proposed a metric representation to evaluate model performance based on two sets of metrics. The first metric is the RMSE of peak phase and amplitude of diurnal rainfall cycle between models and observations. The other metric is the spatial pattern correlations of the first two EOFs between models and observations.

However, several problems may occur when comparing the EOF modes between models and observations to evaluate model performance. This is especially the case when observed mode signals are not well separated in the models, as the derived model EOF mode may represent an entirely different variability from observations. For example, when exploring the interannual and decadal modes, Lee et al. (2019) found that the model-derived EOF may need to be swapped before

TABLE 2. List of 12 CMIP6 coupled atmosphere–ocean climate models.

Model	Description	Spatial resolutions	CPS references
AWI-CM-1.1-MR	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (Germany)	384×192	Tiedtke (1989); Nordeng (1994); Möbis and Stevens (2012)
BCC-CSM2-MR	Beijing Climate Center, China Meteorological Administration (China)	320×160	Wu (2012); Wu et al. (2019)
CESM2	NSF–DOE–NCAR (United States)	288×192	Zhang and McFarlane (1995); Neale et al. (2008)
EC-EARTH3	ICHEC, National University of Ireland (Ireland)	512×256	Tiedtke (1989); Bechtold et al. (2014)
GFDL CM4	NOAA/Geophysical Fluid Dynamics Laboratory (United States)	144×90	Zhao et al. (2018)
GISS-E2.1-G	NASA Goddard Institute for Space Studies (United States)	144×90	DelGenio et al. (2015, 2007)
IPSL-CM6A-LR	Institute Pierre-Simon Laplace (France)	144×143	Emanuel (1991); Rochetin et al. (2014)
MIROC6	JAMSTEC and Atmosphere and Ocean Research Institute (AORI), The University of Tokyo (Japan)	256×128	Chikira and Sugiyama (2010)
MRI-ESM2.0	Meteorological Research Institute (Japan)	320×160	Yoshimura et al. (2015)
NESM3	Nanjing University of Information Science and Technology (China)	192×96	Tiedtke (1989); Nordeng (1994); Möbis and Stevens (2012)
SAM0-UNICON	Seoul National University (South Korea)	288×192	Park (2014)
TaiESM1	Research Center for Environmental Changes, Academia Sinica (Taiwan)	288×192	Zhang and McFarlane (1995); Neale et al. (2008); Wang et al. (2015)

comparison with the observed EOF. Moreover, although diurnal rainfall cycle phases are closely coupled with underlying physical processes, understanding how much the signals that the model can represent in the observed diurnal rainfall helps identify the physical processes that may cause biases. Therefore, in addition to EOF analysis, we also use the CBF method to facilitate model intercomparison. The CBF method projects model anomalies onto the geographical patterns of observed EOFs and provides a map of model anomalies that aligns with observed EOF signals. We summarize CBF method procedures in Table 3 and provide a complete flowchart in Fig. S1 in the supplemental material. The spatial patterns in the EOF/CBF method are rescaled by standard deviation of their principal component (PC) to provide a pattern with unit of rainfall. (It is noteworthy that EOF and CBF patterns of TRMM are exactly the same as in Figs. 3b and 4b and Figs. 5b and 6b.)

After deriving the EOF/CBF patterns, we use pattern correlation coefficient (PCC), absolute RMSE, and spatial normalized RMSE as metrics for our evaluation. By calculating the PCC of model modes with respect to observations, we can determine the quality of simulated patterns of modes of diurnal rainfall cycle in climate models. RMSE indicates the absolute error of the model-simulated pattern and observations, and normalized RMSE is RMSE based on the standardized EOF spatial patterns between observation and models. Comparing RMSE and spatial normalized RMSE can clarify whether RMSE is from errors in spatial patterns or errors in signal magnitude.

Following the methods of Wang et al. (2011), we refer the first leading mode of EOF analysis (i.e., EOF1) as the land–sea contrast mode and the second leading mode of EOF analysis

(i.e., EOF2) as the transition mode. Together, these two modes can represent land, ocean, and coastal regimes (Kikuchi and Wang 2008). We focused on the coastal and land regimes as they make the greatest contributions to total rainfall variation. We compared EOF and CBF analysis results to obtain a more comprehensive evaluation of model performance on prominent diurnal cycle patterns.

3. Performance of diurnal rainfall signals

a. Performance of diurnal rainfall phase and amplitude

Figure 1 shows the model biases of diurnal rainfall amplitude and phase between an ensemble mean of CMIP6, mean of CMIP5, and the observed TRMM dataset. In both CMIP5 and CMIP6 models, the diurnal rainfall bias is mostly homogeneous, with rain peaking early over most land areas and delayed biases found over coastal areas and regions with complex topography (Figs. 1a and 1b). The large early onset biases over land regimes are also found in earlier generations of CMIP (Dai 2006). Regions with diurnal rainfall phases that are largely contributed by convective rainfall produced by cumulus parameterization are also shown in Figs. 1a and 1b. It is clearly seen among CMIP6 models, as in CMIP5, that phase bias is still dominated by convective rainfall. Over most land regimes, cumulus parameterization tends to trigger early onset of convection peaks. In contrast, over tropical coastal regions and areas with complex topography, the diurnal rainfall phase is largely delayed for more than 10 h.

We observed that similar biases in diurnal rainfall amplitude over coastal and continental land regimes shown in CMIP6 as in CMIP5 (Figs. 1c and 1d). The diurnal rainfall amplitude is significantly underestimated in coastal diurnal rainfall regimes

TABLE 3. Summary of conducting common basis function method.

Step 1	Calculate the observed EOFs and normalize to unit variance.
Step 2	The calculation of CBF PCs is to calculate the dot product of observed EOFs and model anomalies spatial pattern at each time steps.
Step 3	At each grid, apply the linear regression to the CBF PCs (from step 2) and model anomalies and get the slope matrix.
Step 4	Construct the representation data of CBFs by multiplying the CBF PCs (from step 2) and the slope (from step 3) and calculate the temporal variance. The percentage of explained variance of CBFs is then calculated by dividing the domain average of temporal variance of constructed CBFs to the total variance.
Step 5	Multiply the standard deviation of CBF PCs (from step 2) and the slope (from step 3) to get the spatial pattern of CBF.

where nighttime rainfall contributes a larger proportion of diurnal rainfall than daytime rainfall (Figs. 1c and 1d). This is especially notable for coastal regimes and on the eastern leeward side of high terrain. In contrast, diurnal rainfall amplitude is overestimated over continental land regions, such as tropical Africa and the Amazon basin, where daytime convection dominates daily rainfall amount (Figs. 1c and 1d). Compared with CMIP5 models, CMIP6 models share similar biases patterns. As the bias of diurnal phases, biases of diurnal amplitude are also attributed from convective rainfall (shown as dotted regions in Figs. 1c and 1d).

Figure 2 shows the bias changes and standard deviation of diurnal rainfall phase and amplitude of CMIP6 models to highlight regions with strong diurnal rainfall cycle uncertainties (i.e., regions where differences are larger than one-half standard deviation). In Figs. 2a and 2c, regions with improved diurnal phase and amplitude of rainfall are shown as blue, and where with more biases is shown as red. In general, CMIP6 models show improvements of the diurnal rainfall phase in most tropical land regions, including the tropical Africa, Asia monsoon region, Amazon basin, and southeast America, while the mean phase gets worse over the ambient oceans, ITCZ, and topographical region (Fig. 2a). The largest standard deviations of diurnal rainfall phase are closely related to coastal regimes and regions with complex topography (Fig. 2b). Interestingly, these regions with large uncertainties are also dominated by significant temporal propagation signals with gradual phase changes in observations (Fig. S2a), which indicates that the models still have large uncertainties when determining propagating diurnal rainfall regimes as shown in phase inconsistency (see Fig. S3). Although the cumulus scheme is still responsible for diurnal rainfall biases (dotted regions in Fig. 1), there are still large inconsistencies in the treatments of convection processes over coastal regions and areas with complex topography (Fig. 2b). CMIP6 models show small improvements over the Central American coastal regions than CMIP5 models, but they have a larger divergence in diurnal rainfall peaks over complex topographical regions (red crosses in

Fig. 2c). The divergence is especially prominent over the sea-side region of coastal regions where mesoscale convective organization prevails.

Figures 2c and 2d show the biases and uncertainty of diurnal rainfall amplitude across the CMIP6 models. Over the tropical oceans, diurnal amplitude in CMIP6 models is in general improved, including the warm pool and storm tracks outside the east coasts of United States and Brazil. Diurnal rainfall amplitude over tropical islands and coastal regions becomes stronger and improved in the ensemble mean of CMIP6 models (Fig. 2c); however, large model divergences are still found over those regions, especially right at the landward side of the coasts of tropical islands (Fig. 2d). Similar to the phase biases, these biases are largely related to the coastal diurnal rainfall regimes, which are attributed to mesoscale convective systems. The most agreeably improved region among CMIP6 models is the tropical Africa region, especially over the afternoon convection regime of the Congo basin. Also interestingly, in CMIP6 models, disagreements are shown over both regions with underestimated amplitude, such as Maritime Continent, and regions with overestimated amplitude such as central Africa and the Amazon basin (Fig. 1d). This suggests that the cause of amplitude biases over these two regions differs among the models. More process studies need to be conducted to understand the mechanisms associated with diurnal convection over these regions.

In general, improvements are found over the tropical land regions where afternoon land convection dominated, showing model improvements in simulating land convection systems. On the other hand, while the ensemble mean biases of phase and amplitude are both improved over the coastal land region, CMIP6 models still have difficulty in simulating diurnal phase over the coastal seaside region. This suggests that more efforts are needed to understand the representation of such coastal raining systems in climate models.

b. Performance of the prominent EOF modes of the diurnal rainfall cycle

To further understand model performance with respect to diurnal rainfall regimes, we performed EOF analysis on climatological diurnal rainfall signals to obtain spatial patterns of diurnal variability. We applied EOF analysis to the CMIP5 and CMIP6 models listed in Tables 1 and 2. For better comparison, all the PCs are rescaled to be unitless, and the corresponding EOFs are spatially normalized to be unit variance and then scaled with the standard deviation of PCs to have the unit of rainfall (i.e., mm day^{-1}). To demonstrate model performance divergence, we use four CMIP6 models—EC-Earth3, GFDL CM4, IPSL-CM6A-LR, and MRI-ESM2.0—as the examples with very different performances to illustrate possible model biases. Of these four selected models, MRI-ESM2.0 and EC-Earth3 represent the “good” group and GFDL CM4 and IPSL-CM6A-LR represent the “not-so-good” group. Such grouping is mainly based on diurnal rainfall cycle performance in the tropics, which will be elaborated in later analysis. The EOF1 of the diurnal rainfall cycle shows an apparent land–sea contrast, with rainfall peaking in the afternoon over land and in the early morning over the ocean (Figs. 3a and 3b). The PCs of the

FIG. 1. Ensemble biases of diurnal rainfall (a),(b) phase and (c),(d) amplitude of CMIP5/CMIP6 compared with the TRMM 3B42 dataset. For phase bias, dotted regions show where the convective rainfall shares the same phase with total rainfall bias. For amplitude bias, dotted regions show where the amplitude bias can be largely contributed to convective rainfall. Only regions with diurnal rainfall amplitude signals larger than the mean diurnal amplitude are shown.

TRMM dataset and all models are plotted in Fig. 3a. The ensemble model-simulated diurnal rainfall mode shows that the PC1 derived from model-simulated rainfall is approximately 2–3 h earlier than that from the TRMM analysis (Fig. 3a). Most models can capture the strong afternoon diurnal rainfall over tropical lands; however, the two good models show more details of the EOF1 pattern, especially for the negative EOF1 region that shows an early morning rainfall peak at around 0900 local time (Figs. 3c and 3d). Such contrast is not seen in the two not-so-good models (Figs. 3e and 3f).

The observed EOF2 pattern shows the strength of nighttime rainfall near midnight in comparison to daytime rainfall near

FIG. 2. (a),(c) Bias differences of diurnal phase (h) and amplitude (%) of CMIP6 models and CMIP5 models compared with TRMM. Amplitude bias is represented as the percentage of absolute bias with respect to the observed amplitude of TRMM. Blue regions show improvements of CMIP6 models compared with CMIP5, and vice versa for red regions. (b),(d) Standard deviations (STD) of diurnal phase and amplitude of CMIP6 models (shaded area) and their differences from that of CMIP5 models (crosses). Blue crosses show where the STD decreases more than 1.5 times, and red crosses show where the STD increases more than 1.5 times in CMIP6 compared to CMIP5.

noon (Kikuchi and Wang 2008). This indicates that strong late-night rainfall occurred over the Maritime Continent, Central America coastal regions, and South America complex topographical regions (Figs. 4a and 4b). Moderate nighttime rainfall signals are shown over the eastern leeward side of high terrain areas, such as the southern Great Plains, Peru, and the Sichuan basin. In contrast, the oceanic side of the Maritime Continent and the leeward sides of mountains in South America show strong afternoon rainfall signals. EC-Earth3

FIG. 3. The first leading PCs and spatial patterns of the first leading EOF (EOF1) of TRMM and four selected CMIP6 models. (a) PCs of four selected models, the ensemble mean of first leading EOF PCs (gray solid line), and the ensemble spread (in ± 1 STD; gray shaded area) of 12 CMIP6 models. (b)–(f) The spatial patterns scaled to be of the unit of rainfall (mm day^{-1}) by normalizing spatial variance to be 1 and then multiplying by the STD of original PC. Anomaly pattern correlations shown in (a) are then scaled to be unitless based on the corresponding spatial pattern.

slightly overestimated magnitude of rainfall over land and had a slightly early onset for phase (Fig. 4c). MRI-ESM2.0 performed the best with respect to both magnitude and phase of the coastal propagation mode (Fig. 4d). Both models have strong early afternoon rainfall signals over central Africa and Amazon basin, which is where models have significant disagreements with the TRMM observation. In contrast, the not-so-good models show very different geographical patterns for EOF2 (Figs. 4e and 4f). These results suggest that the corresponding observed signals may be too weak for EOF analysis to capture. Thus, it is difficult to evaluate the bias from these EOF patterns. This caveat of EOF analysis is also noted in other studies (e.g., Lee et al. 2019). To circumvent this issue, we have used the CBF analysis framework to obtain a more consistent model intercomparison framework.

c. Performance of the prominent CBF modes of the diurnal rainfall cycle

To avoid problems with EOF analysis for model intercomparison, we apply CBF analysis to extract model projections on the observed EOFs. Normalized PCs derived from the models based on the procedure outlined in Table 3 are shown in Fig. 5a, the observed patterns in Fig. 5b, and the model patterns are shown in Figs. 5c–f. As the CBF method focuses on the geographical pattern of EOF modes, it applies standardization to all EOF modes to be zero mean and one standard deviation of each EOF mode to preserve the rainfall units. In this case, Figs. 5b and 6b show the CBF modes of TRMM observations,

which are exactly the same as the EOF modes with the rainfall units in Figs. 3b and 4b.

All CBF PCs are more in phase for EOF1, and geographical modes in the four models are more like the observed mode. The CBF method helps extract the proportion of contrast between tropical oceans and lands described by the observed EOF1, especially for GFDL CM4 and IPSL-CM6A-LR. The CBF method further indicates the weak (strong) PC1 amplitude contrast in GFDL CM4 (IPSL-CM6A-LR), suggesting more (less) late afternoon rainfall needed in the model. Explained variance of the CBF modes also gives a better indication for model performance, as the better group have closer variance with the observed variance (marked on the top-right corner of Figs. 5b–f).

As for EOF2, the corresponding from all four models align with the observed PC but have smaller amplitudes (Fig. 6a). Compared with TRMM observations (Fig. 6b), the most significant differences between the two groups are over the Maritime Continent (Figs. 6c–f). The good group models can also capture the main pattern of nocturnal rainfall over the Maritime Continent, whereas the not-so-good group models still have large daytime rainfall biases. Compared with EOF method, the CBF method better represents this out-of-phase bias between the Maritime Continent and other tropical lands in the not-so-good models.

Figure 7 summarizes the performance of the 12 climate models in the CMIP6 archive in terms of model performance

FIG. 4. The second leading PCs and spatial patterns of the second leading EOF (EOF2) of TRMM and four selected CMIP6 models. (a) PCs of four selected models, the ensemble mean of first leading EOF PCs (gray solid line), and the ensemble spread (in ± 1 STD; gray shaded area) of 12 CMIP6 models. (b)–(f) The spatial patterns scaled to be of the unit of rainfall (mm day^{-1}) by normalizing spatial variance to be 1 and then multiplying by the STD of original PC. PCs shown in (a) are scaled to be unitless based on the corresponding spatial pattern.

metrics of PCC and RMSE for both modes. Models are ordered (left to right) in line with CBF method metrics based on their performance, with better models listed on the left side. CMIP6 models have spatial pattern performances for EOF1 of 0.4–0.8 with CBF analysis and 0.3–0.8 with EOF analysis. The differences in spatial pattern performance between EOF and CBF are trivial for all models except GFDL CM4 and BCC-CSM2-MR (Fig. S4). These two models show significant improvements in both spatial pattern distribution and magnitude error. Moreover, absolute RMSE differences between CMIP6 models are more significant than the normalized RMSE. The RMSE of CBF1 for the CMIP6 models are between 0.2 and 1.1, whereas the spatial normalized RMSEs are between 0.7 and 1.1. For EOF2, PCC metrics range from 0.11 (0.07) to 0.54 (0.53) in terms of correlation coefficients with CBF (EOF) spatial patterns, which is much larger than for EOF1. Compared with RMSE (Fig. 7a), normalized RMSE shows a small divergence between models (Fig. 7c), which indicates that amplitude errors dominate most of model errors.

Performances of temporal regressed patterns to the PCs of EOFs are also shown as the red bars with their ranking marked above in Fig. 7. While the CBF analysis evaluates the model projection onto the observed EOF patterns, the temporal regression analysis examines the model projection onto the observed PC of EOF modes by conducting regressed maps (Figs. S5 and S6). It is not surprised to notice that the temporal regression maps of models are similar to the geographical

projection derived from CBF because of the clear forced response of the land–ocean–atmosphere system to solar radiation. As a result, the PCCs of regressed patterns are also close to those from the CBF method (Fig. 7), suggesting that similar performance ranking in terms of PCC evaluations between the two methods, especially for the EOF1 mode. This result suggests that for most models, the model biases of spatial and temporal variation may come from the misrepresentation of the same processes. The most distinct discrepancy is found in the EOF2 performance of two models, the Alfred Wegener Institute Climate Model, version 1.1, medium resolution (AWI-CM-1.1-MR), and the Nanjing University of Information Science and Technology Earth System Model, version 3 (NESM v3). Both of these models use ECHAM 6.3 model as their atmospheric components with the same CPS designs (Semmler et al. 2020; Cao et al. 2018), thus share very similar patterns of the diurnal phase (Figs. S3a and S3i). The cause of such discrepancy needs further analysis with physical processes simulated in the models, but that is beyond the scope of this study. However, even accounting for changes of these two models, the temporal regression method still suggests the same bifurcation of two model groups that the CBF method shows (red bars in Fig. 7).

d. Overall evaluation of performance of diurnal rainfall cycle

Figure 8 summarizes diurnal rainfall cycle performance by comparing the spatial RMSE and PCC of diurnal amplitude

FIG. 5. The first leading PCs and spatial patterns of the first leading EOF (EOF1) of TRMM and the first leading CBF (CBF1) of four selected CMIP6 models. (a) PCs of four selected models, the ensemble mean of first leading EOF PCs (gray solid line), and the ensemble spread (in ± 1 STD; gray shaded area) of 12 CMIP6 models. (b)–(f) Spatial patterns scaled to be of the unit of rainfall (mm day^{-1}) by normalizing spatial variance to be 1 and then multiplying by the STD of original PC. PCs shown in (a) are scaled to be unitless based on the corresponding spatial pattern.

and CBF modes with those of the observed EOFs. Models with better diurnal amplitude performance are at the bottom right of Figs. 8a and 8b. Diurnal amplitude performance are both improved in the newer CMIP6 versions with respect to spatial pattern PCC and spatial RMSE errors (Figs. 8a and 8b). For the four selected models, all are improved in terms of RMSE and PCC from their CMIP5 versions to their current CMIP6 versions. In general, CMIP6 model performances are closely clustered together, with RMSE of $1\text{--}2 \text{ mm day}^{-1}$ and PCC of $0.4\text{--}0.8$. MRI-ESM2.0 and EC-Earth3 have the best diurnal rainfall amplitude performance.

Figures 8c and 8d show an intermodel comparison for the first two leading CBF modes. Models that better capture CBF patterns are at the top right and those with worse performance are at the bottom left. Compared with CBF2, the models usually have better CBF1 patterns, which range from 0.4 to 0.8 in CMIP5 models (Fig. 8c), and from 0.5 to 0.8 in CMIP6 models (Fig. 8d). In contrast, the PCC of CBF2 is $0.2\text{--}0.5$ in the CMIP5 and $0.1\text{--}0.6$ in CMIP6 models. This result suggests it is more challenging for both generations of models to represent the transition diurnal mode (i.e., CBF2) and associated physical processes. One key feature of CBF2 is that the CMIP6 models are bifurcated, with one group having correlation coefficients larger than 0.3 and the other group having coefficients of $0.1\text{--}0.2$. It is interesting to investigate what makes the differences between the two groups to understand the key to making such improvements. The four selected models are chosen based on this analysis.

Figures 9a and 9b summarize the regions where CMIP6 models are less consistent in terms of the standard deviation of CBF1 and CBF2. Similar analysis is also performed using the EOF analysis method. There are larger uncertainties in climate models over the Maritime Continent, northern South America, and central Africa for both CBF1 and CBF2 (gray shading in Figs. 9a and 9b), which coincides with conclusions drawn from Figs. 5 and 6. The CMIP6 models have more consistent features over the Amazon basin and central Africa than the CMIP5 models, but their magnitudes are more inconsistent over tropical coastal regions, especially for the Maritime Continent. Interestingly, EOF analysis shows a different picture in terms of whether CMIP6 models show improvements (Figs. 9c and 9d). Especially for the transition mode EOF2, this suggests that CMIP6 models have deteriorated rainfall representation over the Amazon basin and central Africa, which differs from what the CBF modes suggest. Based on the geographical patterns CBF and EOF provide, we found the information suggested by the CBF method is more related with the model-simulated signals of the observed modes, showing improvements of rainfall over tropical lands in CMIP6 models.

4. Discussion

Evaluations that use well-selected metrics and methods can provide valuable information on systematic model biases and improve understanding of model capabilities. Here, we applied

FIG. 6. The second leading PCs and spatial patterns of the second leading EOF (EOF2) of TRMM and the second leading CBF (CBF2) of four selected CMIP6 models. (a) PCs of four selected models, the ensemble mean of first leading EOF PCs (gray solid line), and the ensemble spread (in ± 1 STD; gray shaded area) of 12 CMIP6 models. (b)–(f) The spatial patterns scaled to be of the unit of rainfall (mm day^{-1}) by normalizing spatial variance to be 1 and then multiplying by the STD of original PC. PCs shown in (a) are scaled to be unitless based on the corresponding spatial pattern.

two methods, the EOF and CBF methods, to understand the effectiveness of these two methods for evaluating diurnal modes. In summary, they suggest similar skill scores for models with high pattern correlations (Fig. 7 and Fig. S4), but the CBF method gives higher scores than with the EOF methods for those models with larger model biases (Fig. S4). This is because the observed modes may be too weak to be separated by EOF analysis with model anomalies (Lee et al. 2019). This can result in difficulties in providing information for model credibility to represent physical processes underlying the observed modes. Therefore, we suggest that CBF provides a more consistent model intercomparison framework to learn how much models can represent observed modes. Moreover, we also found that the performance of the CBF mode is often in more agreement with that of diurnal amplitude (Fig. 6), better characterizing on geographical contrast between daytime and nighttime rainfall. Additionally, we have examined the regressed daily rainfall cycle with temporal PCs of the observed EOF modes and found that the derived geographical patterns with the PC regression method is very similar to those derived from CBF method (Fig. 7; cf. Figs. 5 and 6 with Figs. S5 and S6). Unlike interannual and intraseasonal variability, diurnal rainfall variability is closely coupled with land–sea–atmosphere interactions in response to the diurnal solar radiation cycle. This result suggests that the biases of geographical patterns and temporal

variation likely share the same source of misrepresentations of these coupled processes.

Comparing model performance between CMIP5 and CMIP6 can provide information about the possible causes of model improvements. To examine the impacts of model resolution on the diurnal rainfall cycle and possible impacts of CPS, we plotted model performance based on metrics of diurnal rainfall cycle with respect to models' resolutions in Fig. 10. The model ensemble suggests the model performance can be benefited from high model resolution based on metrics for diurnal rainfall cycle, including pattern correlations of diurnal phase/amplitude and two EOF modes. Especially for CMIP5 models, pattern metrics in general have a positive correlation with model resolution (Figs. 10a,c,e,g). For most CMIP6 models except BCC_CESM2-MR (denoted as triangular symbols in Figs. 10b,d,f,h), the patterns of diurnal amplitude, phase, and EOF1 are better represented in models with higher model resolution. By comparing the six CMIP6 models with their counterparts in CMIP5, we found that all models show improvements in these three metrics in CMIP6. Among the five models using the same model resolution, CESM2 and MRI-ESM2 have improved their representation of processes related to shallow cumulus with 1° resolution (Yukimoto et al. 2019; Danabasoglu et al. 2020), while GISS-E2.1-G, IPSL-CM6A-LR, and GFDL CM4 improve their model representation of precipitating process with resolution

FIG. 7. The comparison bar charts of model performance between EOF and CBF results of all CMIP6 models listed in Table 2 compared with TRMM data. (a)–(c) Pattern correlations, RMSE, and RMSE with spatial normalized of the first leading EOF (gray frame of bar) and CBF (blue bar) of CMIP6 models and sorted by the performance of CBF results. Corresponding model metrics based on model regressed patterns are shown with red bars and ranking with red numbers. (d)–(f) As in (a)–(c), but of the second leading EOF.

coarser than 1° (Held et al. 2019; Hourdin et al. 2020; Kelley et al. 2020). The EC-Earth3 model also improves its performance with both increasing model resolution and improved cumulus parameterization (Döscher et al. 2021, manuscript submitted to *Geosci. Model Dev.*).

One exception of this positive relation between model resolution is the performance of EOF2 mode (Fig. 10h). While most models with model resolution finer than 1° have better performance, the performance of models with lower resolution is not very consistent. This result is consistent with what found in studies such as Dirmeyer et al. (2011), in which they concluded model performance does not improve when model resolution increases to around 25 km. It is very likely that the current model resolution of CMIP models is still too coarse to resolve the mesoscale convective processes, which is found to greatly attributed to the propagating raining systems over the regions dominated by EOF2. In this case, the ability for CPS to parameterize this regime is important for climate model to simulate EOF2. One example of such improvements is the development from GISS-E2-H to GISS-E2.1-G models and IPSL CM5A-MR to IPSL-CM6A-LR (Figs. 10g,h). Both models have made great efforts in representing temporal variation of convection by improving designs of CPS (DelGenio et al. 2015; Rochetin et al. 2014). While using the same horizontal

resolutions, both models improved EOF2 quite significantly in their CMIP6 versions.

While all methods suggest the bifurcation of model performance of diurnal rainfall cycles among the CMIP6 models, we investigate the cause by looking into the regions with significant observed EOF2 signals. Because the PCs of EOF2 mark strong rainfall contrasts between midnight and early afternoon (Fig. 6a), we examine the contrast in accumulated rainfall between daytime and nighttime in these regions. Figure 11 shows the accumulated nighttime and daytime rainfall averaged over regions with strong positive and negative EOF2 signals. The regions with positive observed EOF2 signal indicate places where daytime rainfall dominates, whereas the negative signal regions indicate places with significant nighttime rainfall. The accumulated daytime rainfall is much larger than the accumulated nighttime rainfall over the positive EOF2 signal areas in the TRMM dataset (leftmost column in Fig. 11a). The four selected models also show dominant daytime rainfall over these regions (Fig. 11a). Both the TRMM dataset and the models show rainfall differences of $3\text{--}5\text{ mm day}^{-1}$ between daytime and nighttime. As for the negative signal regions, the accumulated nighttime rainfall is larger than the accumulated daytime rainfall in the TRMM dataset (Fig. 11b). Although the difference between the daytime and nighttime rainfall in

FIG. 8. Model performance shown as CBF modes derived from climatological diurnal rainfall cycle of CMIP5 and CMIP6. (a),(b) RMSE and pattern correlations of diurnal rainfall range of CMIP5 and CMIP6 models (Tables 1 and 2); (c),(d) pattern correlations of the first leading CBF (DC1) and the second leading CBF (DC2) of the two generations of models.

the TRMM dataset can be as large as 5 mm day^{-1} , the difference in the models is not as distinct as in the observations. In EC-Earth3 and MRI-ESM2, nighttime rainfall surpasses daytime rainfall by a few millimeters per day. The other models show more daytime rainfall than nighttime rainfall. Associated daytime and nighttime convective rainfall is shown as white bars in Fig. 11. The differences in total rainfall are clearly related to rainfall determined by the CPS. Our result indicates that the transition mode model biases are related to spurious daytime rainfall over complex topographical areas and coastal regions. Such overestimation of daytime rainfall may come from cumulus parameterization.

5. Conclusions

This study evaluates the quality of simulated diurnal rainfall cycles from state-of-the-art CMIP6 climate models. We found

that the model-simulated phase and amplitude of diurnal rainfall cycles are generally improved over lands from the CMIP5 models to the CMIP6 models; however, many biases remain in the new-generation CMIP6 models. In terms of amplitude, the models still largely underestimate rainfall amplitude over tropical and coastal regions. The diurnal phase also occurs too early over in those regions, as well as in tropical continental lands and many midlatitude plains adjacent to areas with high terrain. Analysis of agreements in modeled diurnal rainfall phase also shows that the model simulated phase diverges over regions dominated by propagating diurnal systems. Larger phase divergences are found in CMIP6 models, demonstrating that some models have improved but others have not. In the meantime, analysis shows that CMIP6 models agree more on diurnal amplitude on tropical continental land but diverge more over the coasts of the Maritime Continent and the Pacific coast of Central America. Both analyses indicate that the representation of

FIG. 9. STD of the first two leading EOFs of CMIP6 models based on EOF method and CBF method (shaded area), and their differences of STD compared with CMIP5 models (crosses). Blue crosses show where the STD decreases larger than 0.5 STDs, and red crosses show where the STD increase larger than 0.5 STD in CMIP6 compared to CMIP5.

CMIP6 models has generally improved, but more studies are needed to understand the diurnal propagation convection systems and determine how to best represent those systems in climate models.

We used two methods to quantify diurnal rainfall variability with observed modes derived from satellite data. We found that the EOF method with model anomalies may miss observed variability in model simulations if the model-simulated modes are relatively weak. As a supplement, the CBF method better quantifies the projection of model simulated anomalies onto observed modes to extract the associated signals in model simulations. Consistent with previous studies, we found that the CBF method provides a more consistent intermodel

comparison framework, especially for models with weak observed modes. In realization of the importance of temporal variation, we also evaluate the regression method commonly used to correlate climate fields associated with climate variability with PCs associated with observed EOFs. We found that the regression patterns are very similar to the patterns derived with the CBF method in most models, suggesting the models' ability to simulate geographical patterns is well correlated with their ability to simulate EOF PCs. Thus, the model temporal and geographical biases may come from similar misrepresentation of physical processes in the models.

Based on the metrics, positive correlations between model resolution and model performances of amplitude and EOF1 mode of diurnal rainfall cycle are found in all CMIP5 and CMIP6 models. The only exception is for the model performance of EOF2 in CMIP6 models, in which many low-resolution models can have relatively good performance. It is very likely that CPS plays a crucial role in representing EOF2 as the current model resolution of CMIP models are still too coarse to resolve the mesoscale convective processes associated with the propagating raining systems over the regions dominated by EOF2. Moreover, the EOF/CBF analyses found that current CMIP6 model performance is bifurcated based on the representation of the EOF2 spatial patterns associated with convection transition mode. The most significant differences are found in the late night to early morning rainfall patterns over tropical coastal regions and areas with complex topography, especially in the Maritime Continent. By comparing the two model groups of the transition mode (i.e., EOF2), we found that models with lower performance overestimated daytime rainfall in areas where nighttime rainfall prevails in the observations. This suggests that daytime convection over these regions is too strong in these models.

We selected a subset of CMIP6 models whose predecessors were part of CMIP5 to examine progress between the two model generations. We found that the CMIP6 version of models in general improved the representation of diurnal rainfall cycle in terms of diurnal amplitude, phase, and two EOFs. Our results showed that increased model resolution and CPS improvements are both the contributors to improvements between CMIP5 and CMIP6 models. Improving model CPS is beyond the scope of this paper. However, many CMIP6 models have put significant efforts in CPS developments and reported improvements with respect to diurnal cycles (e.g., Lee et al. 2020; Lin et al. 2019; Park et al. 2019). Our results confirm their hard work of model developers has paid off in this new generation of climate models.

Although more analysis is needed to identify the effects of resolution and CPS in diurnal rainfall cycle performance, our results suggest that with current model resolution, CPS remains the dominant cause behind rainfall bias on the diurnal scale. We noticed that despite many improvements in rainfall variability, the spurious daytime rainfall biases found in previous studies remained. This study suggests that more detailed analysis is needed to understand the convective cumulus parameterization of good models to understand key designs for cumulus parameterization for simulating

FIG. 10. Scatterplots to show the relationship between model resolution (y axis) and model metrics for diurnal rainfall cycle (x axis) for both (left) CMIP5 and (right) CMIP6 models. The model metrics are defined as the PCC of (a),(b) amplitude, (c),(d) diurnal phase, (e),(f) CBF1, and (g),(h) CBF2. The BCC_CESM2-MR model discussed in the text is shown as triangles in (b), (d), and (f).

FIG. 11. Comparison of model-simulated accumulated nighttime rainfall (1800–0600 LT) and daytime rainfall (0600–1800 LT) over regions with strong (a) positive and (b) negative signals of transition mode (EOF2) found in TRMM. Blue bars show the accumulated nighttime rainfall, red bars show the accumulated daytime rainfall, and white bars show the respective accumulated convective rainfall. The y axis denotes the rainfall (mm day^{-1}), while the x axis denotes TRMM and four selected CMIP6 models.

propagation regimes, with a focus on how to suppress spurious daytime rainfall where such systems prevail.

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