Improved Tropical Modes of Variability in the NCEP Climate Forecast System (Version 2) via a Stochastic Multicloud Model

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ABSTRACT

A stochastic multicloud model (SMCM) convective parameterization, which mimics the interactions at subgrid scales of multiple cloud types, is incorporated into the National Centers for Environmental Prediction (NCEP) Climate Forecast System, version 2 (CFSv2), model (CFSsmcm) in lieu of the preexisting simplified Arakawa–Schubert (SAS) cumulus scheme. A detailed analysis of the tropical intraseasonal variability (TISV) and convectively coupled equatorial waves (CCEWs) in comparison with the original (control) model and with observations is presented here. The last 10 years of a 15-yr-long climate simulation are analyzed. Significant improvements are seen in the simulation of the Madden–Julian oscillation (MJO) and most of the CCEWs as well as the Indian summer monsoon (ISM) intraseasonal oscillation (MISO). These improvements appear in the form of improved morphology and physical features of these waves. This can be regarded as a validation of the central idea behind the SMCM according to which organized tropical convection is based on three cloud types, namely, the congestus, deep, and stratiform cloud decks, that interact with each other and form a building block for multiscale convective systems. An adequate accounting of the dynamical interactions of this cloud hierarchy thus constitutes an important requirement for cumulus parameterizations to succeed in representing atmospheric tropical variability. SAS fails to fulfill this requirement, which is evident in the unrealistic physical structures of the major intraseasonal modes simulated by CFSv2 as documented here.

1. Introduction

The tropical atmosphere harbors a spectrum of dynamical modes that interact with each other and with climate systems on multiple spatial and temporal scales (Moncrieff and Klinker 1997; Kiladis et al. 2009; Lau and Waliser 2011). It is still debatable whether these different modes are part of a monster tropical convection belt or are separate components (Toma and Webster 2010a, b; Serra et al. 2014). The Madden–Julian oscillation (MJO; Zhang 2005, 2013) and monsoon intraseasonal oscillations (MISOs; Goswami 2012) dominate tropical variability on intraseasonal time scales, and convectively coupled equatorial waves (CCEWs) and tropical depressions of all sorts are seen on synoptic scales (Kiladis et al. 2009). While CCEWs are thought to be the moist analogs of equatorially trapped waves—linear modes of equatorial dynamics (Matsuno 1966; Takayabu 1994; Wheeler and Kiladis 1999), there is no dry dynamical equivalent mode for the MJO. The atmospheric science community is still debating whether the MJO is a moisture-coupled planetary-scale mode or some sort of a multiscale convective envelope owing its existence to upscale energy transfer from synoptic and mesoscale systems (Majda and Stechmann 2009a; Wang and Liu 2011; Sobel and...
Maloney 2012; Thual and Majda 2015; Stachnik et al. 2015). Nonetheless, there is a consensus in the climate modeling community that a climate model’s ability to simulate the weather and climate realistically depends largely on its ability to simulate these intraseasonal and synoptic-scale modes (Lin et al. 2006; Hung et al. 2013; Jiang et al. 2015). This study aims to gauge, in this regard, the U.S. National Centers for Environmental Prediction Climate Forecast System, version 2 (CFSv2), in which the stochastic multicloud model (SMCM) convective parameterization of Khouider et al. (2010, hereafter KBM10) is implemented (Deng et al. 2015) in comparison to the original CFSv2 model. In the sequel, the acronym CFSv2 is used to designate the original (control) model while the modified model, using the SMCM parameterization, is termed CFSsmcm.

Despite the significant progress of the last decade or so (Moncrieff et al. 2012, and references therein), present-day global climate models (GCMS) still show limited ability in simulating the MJO (Slingo et al. 1996; Lin et al. 2006; Kim et al. 2009; Hung et al. 2013; Jiang et al. 2015), MISOs (Waliser et al. 2003; Lin et al. 2008b; Sabeerali et al. 2013; Sperber et al. 2013), and CCEWs (Lin et al. 2008a; Straub et al. 2010; Hung et al. 2013; Guo et al. 2015). The inefficiency of the present-day climate models to simulate these tropical intraseasonal variability (TISV) modes stems from our limited understanding of tropical dynamics. Recent studies emphasize the importance of representing processes that are thought to be important for TSIV dynamics, including moisture preconditioning, atmosphere–ocean coupling, cloud radiative feedback, convective momentum transport, stratiform heating, and boundary layer dynamics (Lin et al. 2006; Straub et al. 2010; Jiang et al. 2015; Wang et al. 2016; Moncrieff et al. 2017). Nonetheless, there is a consensus in the climate modeling community that the fidelity in proper simulation of the MJO is a pinnacle metric to assess the fidelity of a GCM (Waliser et al. 2009). Straub et al. (2010) found that 75% of the Coupled Model Intercomparison Project (CMIP) phase 3 models fail to realistically simulate the convectively coupled Kelvin waves. Although the MJO and the CCEWs have a lot in common, improvement in one does not necessarily translate into improvement in the other despite the undeniable evidence that CCEWs, the MJO, and mesoscale convective systems are embedded in and interact with each other across multiple temporal and spatial scales (Nakazawa 1988; Moncrieff and Kinter 1997; Gottschalck et al. 2013; Dias et al. 2013). Moreover, both the MJO and the MISO are believed to have an impact on the global weather and climate (Krishnamurthy and Kinter 2003; Zhang 2005, 2013; Lau and Waliser 2011). From clustering synoptic systems (Goswami et al. 2003) to influencing ENSO development (Kirtman and Shukla 2000), TISV modes have profound effects on tropical variability, the impact being felt much beyond their own spatial and temporal scales. Therefore, a model that simulates these TISV modes (viz., MJO, CCEW, and MISO) realistically is expected to simulate the mean state and many other aspects of the global climate with fidelity (Jiang et al. 2015; Kim et al. 2009; Waliser et al. 2009).

The inability of the present-day climate models to accurately simulate the prominent TISV modes is often attributed to their inability to simulate the mean climate state and vice versa (Slingo et al. 1996; Sperber et al. 1997; Waliser et al. 2003; Sperber 2004; Lin et al. 2006; Zhang et al. 2006). Although the relationship between the TISV modes and the mean climate state has been the topic of many studies, that of the synoptic variability and the mean has gotten comparatively less attention. Recently, using 36 coupled models (including 32 CMIP phase 5 models), Goswami and Goswami (2017) argued that the lack of simulated synoptic variability is at least partially responsible for the precipitation dry bias in rain-abundant regions of the tropics. The deterministic nature of the convective parameterization (CP) schemes used in those models is to blame to some extent, because of their limited ability to accurately represent the sub-grid-scale convective elements (Arakawa 2004). For an overview of the convection parameterization problem, see Plant and Yano (2015a,b). One way of realistically representing the many possible realizations of the sub-grid-scale convective processes is by explicitly resolving the cloud and convective processes (Grabowski and Smolarkiewicz 1999; Grabowski 2001; Khairoutdinov and Randall 2001; Randall et al. 2003; Satoh et al. 2008; Fudeyasu et al. 2008; Benedict and Randall 2009; Liu et al. 2009). While superparameterized and global cloud-resolving models continue to evolve (Goswami et al. 2015; Yashiro et al. 2016; Fukutomi et al. 2016; Kooperman et al. 2016), they remain computationally expensive and impractical. For practical reasons, at the least, stochastic approaches (Buizza et al. 1999; Lin and Neelin 2000, 2002, 2003; Palmer 2001; Majda and Khouider 2002; Khouider et al. 2003; Plant and Craig 2008; Teixeira and Reynolds 2008; KBM10) are getting more and more consideration (Deng et al. 2015, 2016; Ajayamohan et al. 2016; Davini et al. 2016; Goswami et al. 2017b, hereafter GKPM17b; Dorrestijn et al. 2016; Wang et al. 2016; Gottwald et al. 2016; Bengtsson and Körnich 2016; Berner et al. 2016; Peters et al. 2017) as a computationally cheap alternative. While it is perhaps too early to posit stochastic approaches as the ultimate solution to the convective...
parameterization problem, they remain a favorable option for operational purposes (Plant et al. 2015) and also as a “laboratory tool” to tackle the convective parameterization problem. In this paper, we use the SMCM of KBM10 as a cumulus parameterization for the first time in a comprehensive GCM.

Previous studies involving the SMCM (KBM10; Khouider et al. 2011; Ajayamohan et al. 2013, 2014, 2016; Deng et al. 2015, 2016) have shown considerable skill in simulating TISV. Using the deterministic multicloud model (DMCM) of Khouider and Majda (2006, hereafter KM06; see also Khouider and Majda 2008b) as a cumulus parameterization in the National Center for Atmospheric Research (NCAR)’s High-Order Methods Modeling Environment (HOMME), at coarse GCM resolution, Khouider et al. (2011) demonstrated that the DMCM could simulate many observed features of TISV modes, such as the MJO and CCEWs. Ajayamohan et al. (2013) showed that when a warm-pool-like background is imposed, the same model exhibits realistic initiation and dynamics of the MJO via circumnavigating Kelvin waves. Deng et al. (2015, 2016) showed that when the SMCM is incorporated into HOMME in an aquaplanet setup, it produces MJOs with dynamical features such as the front-to-rear vertical tilt and the quadruple vortex structure (Kiladis et al. 2005) and realistic intermittent variability. Ajayamohan et al. (2014, 2016) showed that the simulation of MISOs can be improved by incorporating the SMCM or its deterministic version in the NCAR HOMME aquaplanet model. However, all of the above results are based on idealized aquaplanet simulations. Therefore, implementing the SMCM in a fully coupled climate model is an obvious way forward. We took up the NCEP CFSv2 model, promoted by the National Monsoon Mission of the Ministry of Earth Sciences, India, and implemented SMCM in it. Namely, we have replaced the conventional convective parameterization used by CFSv2, which is the simplified Arakawa–Schubert (SAS; Pan and Wu 1995; Pattnaik et al. 2013), by the SMCM model. The details of this implementation, including the parameter tuning, can be found in GKPMM17a and Goswami et al. (2017a, hereafter GKPMM17b).

The paper is organized as follows: A brief description of the SMCM model formulation is presented in section 2. Section 3 describes the results, particularly emphasizing the dynamical and physical features of TISV modes, namely, the MJO, CCEW, and MISO, as simulated by CFSsmcm in comparison to the control CFSv2 model and observations. Finally, some discussion and concluding remarks are given in sections 4 and 5, respectively.

2. Model equations, data, and methodology

At this experimental stage of the SMCM parameterization approach, the convective heating profile is based on three prescribed basis functions, which are designed to mimic the three dominating cloud types of tropical convection, namely, congestus, deep, and stratiform (Johnson et al. 1999; Mapes et al. 2006). The SMCM divides each GCM grid box into a 40 × 40 microscopic lattice. Each lattice site is either occupied by congestus, deep, or stratiform cloud decks, or it is a clear-sky site. Transitions from a lattice site with one type of cloud to another type occur according to a stochastic Markov chain process whose transition probabilities depend on the large-scale state through a few convection predictors. New to the CFS implementation (GKPMM17a; GKPMM17b), the large-scale predictors include the convective available potential energy (CAPE), convective inhibition (CIN), midtropospheric (700 hPa) dryness/moistness (MTD), and vertical velocity at the top of the boundary layer W. Each microscopic lattice within a large-scale grid box sees the same large-scale conditions. However, their evolutions in time differ as the transition rules also depend on the previous state of a microscopic lattice, which provides time memory for the cumulus parameterization. The heating rates associated with the three cloud types are parameterized through closure formulas, depending on midlevel moisture and CAPE, which are proportional to the cloud area fractions obtained through the evolving stochastic lattice model. The three prescribed basis functions of the SMCM are amplified by the respective parameterized heating rates, and the amplified profiles add up to yield the total parameterized heating. The moisture and temperature tendencies are calculated from this parameterized total heating and then given back to the host model, which is CFSv2.

Specifically, the total convective heating is expressed as (Khouider et al. 2011):

$$Q_{tot}(z) = H_d \phi_d(z) + H_c \phi_c(z) + H_s \phi_s(z).$$

Here, $H_d$, $H_c$, and $H_s$ are the parameterized heating rates associated with the three cloud types, congestus, deep, and stratiform, respectively, while $\phi_d$, $\phi_c$, and $\phi_s$ are the corresponding heating profile basis functions. Further, we have

$$H_d = \sigma_d Q_d, \quad H_c = \sigma_c Q_c, \quad H_s = \sigma_s Q_s,$$

where $Q_d$, $Q_c$, and $Q_s$ are the parameterized heating potentials depending deterministically on CAPE and midlevel moisture, and $\sigma_d$, $\sigma_c$, and $\sigma_s$ are the stochastic area fractions (lattice coverage) occupied by the respective cloud types. These cloud area fractions, along
with a fourth state of sky condition with no clouds, describe a Markov jump stochastic process in the form of a multidimensional birth–death system whose transition probabilities depend explicitly on some key large-scale predictors motivated by observations and physical intuition (KBM10; Frenkel et al. 2012; De La Chevrotière et al. 2015; Deng et al. 2016). The temperature and moisture convective tendencies are set according to et al. 2015; Deng et al. 2016). The temperature and moisture convective tendencies are set according to $Q_{tot}$. While, as already mentioned, further details about the implementation of the SMCM convective parameterization in CFSv2 can be found in GKPMM17a and GKPMM17b, we note here that except for replacing the SAS cumulus scheme with SMCM, the rest of CFSv2 configuration is unchanged. For instance, CFSsmcm still uses the same shallow cumulus scheme as CFSv2. It has to be noted that while the SMCM accounts for cumulus congestus clouds that are shallow, compared to deep cumulonimbus clouds that exceed the freezing level and sometimes reach the tropopause (Johnson et al. 1999), it does not represent what are traditionally known as shallow cumulus clouds, which are confined near the top of the atmospheric boundary layer, typically below the trade inversion (Siebesma et al. 2003; Zhao and Austin 2005a,b; Stevens 2006; de Roode et al. 2012; Dorrestijn et al. 2013; Waite and Khouider 2009). However, unlike the SAS scheme, the SMCM implementation ignores radiative feedback from the parameterized clouds. The latter may be included in future versions of CFSsmcm by taking advantage of the stochastic cloud area fractions. Details on the reference model CFSv2 are available in Saha et al. (2014).

We have analyzed the last 10 years output from a 15-yr CFSsmcm climate simulation in comparison with a simulation of the same length and same initial conditions, done with the original model, CFSv2, using the SAS convection scheme as a control run. As an observational benchmark, we used outgoing longwave radiation (OLR) from NOAA (2.5° × 2.5°; daily; Liebmann and Smith 1996) and the thermodynamical and dynamical parameters from NCEP reanalysis (2.5° × 2.5°; daily; Kalnay et al. 1996) to evaluate the model-simulated climate using either SMCM or SAS.

For both CFSsmcm and CFSv2 simulations, we used a horizontal resolution of T126, 64 vertical levels, and a time step of 10 min. We have extensively used the wavenumber–frequency filtering technique introduced and used by Kiladis et al. (2005, 2009) to isolate the different modes of tropical ISV and CCEWs.

3. Results

In GKPMM17a, the CFSsmcm simulation is found to have a reasonably good mean state, at least as good as the control CFSv2 model if not better in some aspects, especially in places where CFSv2 is known to have significant biases. Given that CFSv2 is one of the better state-of-the-art climate models, this is a satisfactory result. In this section, the tropical intra-seasonal variability in the CFSsmcm simulation is documented. One standard metric to assess a model-simulated ISV is to plot the Takayabu–Wheeler–Kiladis (TWK) spectra (Takayabu 1994; Wheeler and Kiladis 1999). Figure 1 shows the TWK spectra plotted for the model-simulated OLR for both CFSv2 and CFSsmcm and observations (NOAA OLR; Liebmann and Smith 1996).

The observed modes have a wealth of literature available for their documentation (Takayabu 1994; Wheeler and Kiladis 1999; Kiladis et al. 2009, and references therein). However, for the sake of completeness, it is worthwhile to list the prominent modes, corresponding to the most significant peaks in Figs. 1b and 1e. In the symmetric part of the spectrum, we have the eastward-moving MJO corresponding to the peak at wavenumbers 1–3 and time periods between 30 and 60 days, westward-moving $n = 1$ equatorial Rossby (ER) wave peak from wavenumber $−3$ to $−4$ and time period of $−30$ days, Kelvin waves with an elongated peak spanning wavenumbers 2–7 and time periods from 4 to 10 days, and $n = 1$ westward inertia gravity (WIG) waves roughly from around wavenumber $−1$ to $−15$ and a time period of 3 days. The antisymmetric part shows one dominant corresponding to westward mixed Rossby–gravity (MRG) waves, between wavenumbers 0 and $−6$ and time periods from 3 to 6 days, and eastward inertia gravity (EIG) waves for wavenumbers 0–8 and time periods between 2 and 5 days. The remaining power blobs at negative wavenumbers sandwiched between the WIG and ER waves are believed to correspond to tropical depressions of all sorts including monsoon low-pressure systems (Wheeler and Kiladis 1999).

The TISV modes are not prominent in the CFSv2 simulation as indicated by the lack of color contrast in the plots, Figs. 1c and 1f. Except for the ER waves, CFSv2 underestimates the power for all the other prominent modes. Moreover, the CFSv2 MJO peak has a longer time period than observations (Fig. 1b). Significant improvement is evident in the CFSsmcm simulated TWK spectra (Figs. 1a,b), including the MJO and especially the higher-frequency CCEWs, mentioned above. The MJO period and strength has substantially improved. Also, the Kelvin wave and $n = 1$ WIG power have clearly improved in the CFSsmcm. There is a discernible peak corresponding to MRG waves in the CFSsmcm run, while it is
nonexistent in CFSv2. Nonetheless, CFSsmcm simulates a weaker power for most of these modes compared to observations, and thus, there is still room for improvement.

While they obey a rough self-similarity feature in vertical structure (Mapes et al. 2006; Kiladis et al. 2009; Khouider et al. 2011), the MJO and the other convectively coupled waves have different propagation properties and different structural details and physical features. The MJO has been one of the most highly studied climate phenomena (Zhang 2005; Wang et al. 2016, and references therein). A review of CCEWs can be found in Kiladis et al. (2009). The state-of-the-art models show limited ability in simulating these essential features of the tropical ISV (Lin et al. 2006, 2008b,a; Straub et al. 2010; Hung et al. 2013; Guo et al. 2015; Wang et al. 2016). Guo et al. (2015) argues that there is a good chance that a model that simulates the CCEWs realistically would simulate a “good” MJO as well. Therefore, for an in-depth analysis of TISV in CFSsmcm simulations, we isolate the MJO and the different CCEWs applying space–time filtering (Kiladis et al. 2009) and examine the different features. We repeat the same exercise for observations and the CFSv2 control simulations for a proper assessment of the improvements.

a. MJO

We applied space–time filtering on different meteorological fields, and we retained the averaged signal corresponding to wavenumbers 1–9 and time period of 30–96 days, following Kiladis et al. (2005). We isolated the MJO-filtered anomalies for OLR and zonal and meridional wind fields for both the CFSsmcm and the control–CFSv2 simulations and observations (NOAA OLR and NCEP winds; Kalnay et al. 1996). In Fig. 2, the daily variance, for the full year, of the MJO-filtered OLR anomalies are shown. In observations (Fig. 2b), the maximum variance is seen over the warm waters of the Indian Ocean and western Pacific Ocean, with the peak located over the equatorial Bay of Bengal. In the western Pacific Ocean, the amplitude is asymmetric about the equator, tilting southward. This is possibly due to the interaction of the MJO with the warm waters of the Indonesian throughflow (Zhou and Murtugudde 2010; Zhang 2013). There is an isolated peak off the Gulf of California. In the CFSsmcm simulation (Fig. 2a), the overall variance looks weaker than in observations. The
variance pattern over the Indian Ocean is reasonably well simulated with the peak slightly shifted southwestward. Over the western Pacific, the pattern appears patchy with an underestimation toward the southern branch, but it remains qualitatively similar to the observations. The peak off the Gulf of California is captured well; however, one more isolated peak is visible over the southeast Atlantic. In the CFSv2 simulation (Fig. 2c), the MJO variance splits into two streaks, distributed north and south of the equator (Fig. 2b). Moreover, the variance is marginally stronger over the west Pacific than over the Indian Ocean, unlike the observations and the CFSsmcm run. Similarly, while a variance pattern is evident, a remnant of the double ITCZ problem is also seen. Overall, CFSsmcm simulated MJO daily variance has greatly improved qualitatively compared to the CFSv2 control simulation.

Figure 3 shows snapshots of an MJO phase composite in terms of the MJO-filtered OLR for different lead times. To construct the composite, the peak MJO dates are identified based on an MJO index, corresponding to the MJO-filtered anomalies taken at a location of corresponding high variance. We have checked that the results are resilient to changes in location of this index. The center column of Fig. 3 shows the propagation of the MJO-filtered OLR anomalies from observations. At 15 days lag, a blob of convection occurs over the west equatorial Indian Ocean (around 60°E). The blob makes a smooth migration eastward and reaches 180°E at a lead time of 25 days. Thus, the convection describes 120° of longitude in 40 days, which corresponds to a phase speed of approximately 5 m s⁻¹. During the decay process of the blob, it spreads out and separates into two blobs south and north of the equator (lead 25 days).

In the left column of Fig. 3, the phase composite of CFSsmcm simulated MJO-filtered OLR anomalies are shown. The overall features of the propagation of convection are reasonably captured. However, there are a few striking discrepancies. The first to catch the eye are a smaller spatial extent of the blob and a slower phase...
speed. Moreover, the active convection over the central Pacific at 5 days lag seems unrealistic, but it is very weak. A closer look at this active convection over the central Pacific reveals a wavy pattern indicated by deepening and fading blue shading alternately. This possibly indicates a contamination of the MJO signal by some other modes of variability inherent to CFSsmcm. In comparison, for the CFSv2 MJO-filtered OLR

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**FIG. 3.** MJO phase propagation. Composite of different phases of the MJO-filtered OLR (W m\(^{-2}\)) anomalies constructed based on an MJO index averaged over 82.5°–90°E and 0°–8.5°N. (left) CFSsmcm, (center) observations, and (right) CFSv2. Phase-lag stamps are seen in the bottom-right corner.
anomalies (right column of Fig. 3), the detailed features hardly resemble the observations. The amplitude and organization of convection are very weak, making it extremely difficult to comment on the phase speed or any other physical property. The weak amplitude of the MJO phases in CFSv2 in Fig. 3, despite a relatively strong variance seen in Fig. 2c, is due to the strong suppressed phase of MJO in CFSv2 simulations compared to the observations and to the CFSsmcm simulation, which present rather stronger active phases.

The propagation features of the MJO are arguably better characterized by the Hovmöller plots of the MJO composite averaged over the latitude band between 10°S and 10°N, shown in Fig. 4. The top three panels, Figs. 4a–c, show the composites of the MJO-filtered anomalies, and the bottom three panels, Figs. 4d–f, show the composite of the corresponding raw (unfiltered) data anomalies for CFSsmcm, NOAA OLR, and the CFSv2 control simulation, respectively. Consistent with Fig. 3 (left column), a smooth propagation is exhibited by the observed OLR data. A feature, which was not evident in Fig. 3 and appears clearly in Fig. 4b, is the different phase speeds of the MJO over the Indian Ocean and Pacific Ocean basins. The MJO phase speed is faster over the west Pacific compared to that over the Indian Ocean. In the CFSsmcm simulation (Figs. 4a,d), the phase speed of the MJO appears slower than observed over the Indian Ocean, and the organization is weaker over the west Pacific. Focusing on the MJO-filtered anomaly composite Hovmöller plot (Fig. 4a), the organization almost seems broken past the Maritime Continent and reappears in the central Pacific with a hint of eastward movement from there indicating a wavenumber-2 structure. However, when we observe closely the unfiltered composite in Fig. 4d, the CFSsmcm simulation appears to capture the two different phase speeds on the two sides of the Maritime Continent, especially for the active phase of convection (blue shading). In the CFSv2 simulations (Figs. 4c,f), however, both the organization and amplitude are poorly simulated, consistent with Fig. 3 (right column).

Figure 5 shows the circulation features at 850 hPa (Figs. 5a–c) and at 200 hPa (Figs. 5d–f) of the MJO-filtered anomalies for the observations and the two model simulations, as indicated. The observed circulation pattern at 850 hPa (Fig. 5b) shows a pair of Rossby
gyres north (counterclockwise) and south (clockwise) and slightly west of the convection peak location with a broad fetch of easterlies over the equatorial Pacific. Two other gyres of opposite signs are also visible east of the convection center, but their centers are located far away from the equator—outside the displayed domain. This structure constitutes the famous quadruple structure of the MJO reported in many observational and theoretical studies of the MJO (Rui and Wang 1990; Hendon and Salby 1994; Majda and Biello 2003; Kiladis et al. 2005; Zhang 2005; Majda and Stechmann 2009b). At 200 hPa (Fig. 5e), subtropical quadruple rotational circulation enveloping the convective center and winds diverging out of the convection center are seen. The observed circulation patterns at 850 and 200 hPa indicate a dominantly baroclinic (reversal of wind direction with height) vertical structure for the MJO-filtered anomalous winds.

The CFSsmcm simulation (Figs. 5a,d) indeed appears to capture this baroclinicity to a good extent. However, the circulation patterns themselves, both at 850 (Fig. 5a) and 200 hPa (Fig. 5d), are not as well organized as in observations, which is consistent with the aforementioned wavenumber-2-type structure of the CFSsmcm simulated MJO. Nevertheless, CFSsmcm captures the major features considerably well: at 850 hPa (200 hPa), the Rossby gyres (anticyclonic circulations) meridionally placed at the two wings of the convection maxima at around 70°–80°E, underdeveloped in the southern (northern) hemisphere, with westerlies (easterlies) over the Indian Ocean Basin and easterlies (westerlies) over the Pacific basin. For the CFSv2 simulations (Figs. 5c,f), the circulation patterns look too disorganized to make any conclusive remark.

Figure 6 shows the composite of OLR time series (top panels) and vertical structure of the MJO-filtered anomalies, averaged over 5°S–5°N, for CFSsmcm (left column), observations (center column), and CFSv2 (right column). For a better visualization, each column is topped with its respective OLR variations to locate the convection maximum. It is not hard to see that CFSsmcm simulates the convection activity more realistically than CFSv2. The observed features around the convection maximum (OLR minimum in Fig. 6b), like the quadruple structure of horizontal wind in the zonal cross section (Fig. 6e), convergence (divergence) at the lower (upper) troposphere collocated with the OLR minimum (Fig. 6h), leading (following) negative (positive) humidity anomalies led by a lower-level moistening (Fig. 6k), the collocated
Fig. 6. Longitude–height cross section (averaged for 5°S–5°N) of MJO composite of the MJO-filtered (a)–(c) OLR (W m\(^{-2}\)) anomalies and the corresponding anomalous (d)–(f) zonal wind (m s\(^{-1}\)), (g)–(i) convergence (s\(^{-1}\)), (j)–(l) relative humidity (%), (m)–(o) temperature (K), (p)–(r) vertical velocity (Pa s\(^{-1}\)), and (s)–(u) diabatic heating rate (K day\(^{-1}\)). (left) CFSsmcm simulation, (center) observations (NOAA OLR), and (right) CFSv2.
positive temperature anomalies (Fig. 6n), the colocated updraft with surrounding subsidence (Fig. 6q), and the colocated positive anomalous diabatic heating with an extension ahead of the convection maximum in the lower levels (Fig. 6l), are reasonably well captured in the CFSsmcm simulation. However, the convergence remains as noisy as in the default CFSv2, as both simulations lack the smoothness of the observed convergence field. Also, the vertical velocity (Fig. 6p) and the apparent heat source (Fig. 6s) look even noisier than the default CFSv2. This is consistent with the overestimated daily variance simulated by even noisier than the default CFSv2. This is consistent with the overestimated daily variance simulated by the CFSsmcm model (Fig. 1 of GKPM17a).

The westward tilt (Zhang 2005; Kiladis et al. 2005) prominent in the zonal wind (Fig. 6d), convergence (Fig. 6g), relative humidity (Fig. 6j), and temperature anomalies (Fig. 6m) are also captured to a good extent by CFSsmcm. However, the CFSsmcm fields are somewhat noisy and have weaker amplitudes. CFSv2 shows limited skill in capturing these features, lacking severely in simulating the adequate organization and amplitude. Noteworthy, in the CFSv2 simulation, the anomalies corresponding to the suppressed phase of convection (OLR maximum) look more prominent than the active phase. This is clearly visible on the top panels where CFSv2 exhibits a strong OLR positive peak ahead of the convection center and not much of a minimum OLR peak, contrary to CFSsmcm, which is consistent with the observations, with a caveat that the OLR maximum is ahead of the minimum in the observation but the former lags the latter in CFSsmcm. Nonetheless, this difference is perhaps simply an artifact of the compositing technique.

**b. CCEW**

To verify whether the structure and propagation features of the simulated CCEW modes are well simulated, here, we isolate the different individual modes by applying a space–time filtering and examine the different features as done for the MJO. The space–time filters used here are the same as the ones used in Kiladis et al. (2009), except for the $n = 0$ EIG waves for which we used a narrower region, limited by wavenumbers 1–3, frequencies 0.166–0.55, and equivalent depth curves $H = 12$ and 50 m. A broader filter as in Kiladis et al. (2009) makes the EIG signal contaminated with Kelvin waves, as the latter appear stronger in the CFSsmcm simulation. An alternative would be to separate the solution into symmetric and antisymmetric parts, but we refrained from doing that here because it is not standard practice.

Figure 7 shows the daily variances corresponding to the different modes of the CCEW spectrum for the CFSsmcm simulation (left column), observations (middle column), and CFSv2 simulation (right column). The maximum variance for all the displayed modes is observed to be over the west to central Pacific region. In the CFSsmcm simulations (left column) the overall pattern and amplitude of the different variances are well captured; however, the peak variance is slightly shifted westward for almost all the modes. Variance for the Kelvin, EIG, and MRG modes is slightly underestimated, whereas that of the ER and WIG are slightly overestimated. The CFSv2 (right column) severely underestimates the daily variance for all the modes, except ER waves, which are overestimated, on the contrary. CFSsmcm also simulates an overestimated ER daily variance, but the CFSv2 overestimation is larger. The black lines are drawn to highlight the maximum variance region, over which the composite anomalies are averaged to explore the propagation features of the different CCEWs in Fig. 8.

The propagation features, shown in Fig. 8, are captured reasonably well by CFSsmcm: eastward-propagating Kelvin and EIG waves and westward-propagating ER, WIG, and MRG waves. The phase speeds are simulated marginally slowly (more so for the EIG waves), except for the MRG waves. The westward shift of the maximum variance, observed in CFSsmcm simulations in Fig. 7, is now prominently visible. In fact, the slower phase speeds are maybe connected to this westward shift. Overestimation of ER waves is also more evident now. Except for the ER waves, CFSv2 simulated CCEWs have weak amplitudes. The most striking improvements are seen in the simulation of the Kelvin, inertia gravity, and MRG waves by CFSsmcm compared to CFSv2.

The 850- and 200-hPa composite circulation patterns corresponding to the peak phase of the different CCEWs are shown in Figs. 9 and 10, respectively, superimposed on the corresponding OLR anomalies. The observed circulation features are reasonably well simulated by the CFSsmcm simulation, including equatorial low-level westerlies and low-level easterlies convergent to the active convection center for the Kelvin wave (Fig. 9b), a train of cyclonic and anticyclonic circulation patterns flanking both sides of the equator and collocated with the active and suppressed centers of convection for the ER wave (Fig. 9e), and a train of cyclonic and anticyclonic circulations over the equator binding the convective centers located on the four quadrants of the circulation pattern for the MRG wave (Fig. 9n). The simultaneous meridional and zonal convergent streamlines in the Kelvin wave composites in the CFSsmcm and to some extent in the observations are consistent with the structure of Kelvin waves evolving in a meridional...
jet shear background (Roundy 2008; Ferguson et al. 2009; Han and Khouider 2010). For the ER (Fig. 9d) and MRG (Fig. 9m) waves, the convection is underdeveloped south of the equator. Also the location of the simulated convective centers corresponding to the ER wave (Fig. 9d), in the Northern Hemisphere, are shifted considerably south of the observed locations (Fig. 9e).
In the CFSv2 simulated climate, the pattern of the OLR anomalies are realistically captured; however, they are underestimated, except for the ER waves, which is consistent with Figs. 7 and 8. Also, except for the ER (Fig. 9f) and MRG (Fig. 9o), the model misses the major circulation features. The WIG (Fig. 9l) waves particularly look very poorly simulated. At 200 hPa, the observed winds (Fig. 10, center column) are reversed relative to 850-hPa winds because of baroclinicity and are relatively stronger than at 850 hPa. The improvements in the winds at 200 hPa are consistent with the improvements seen in the 850-hPa level in CFSsmcm simulations. To avoid redundancy, we are keeping away from a detailed description of the features observed at the 200-hPa level. Realistic circulations at lower (850-hPa) and upper (200 hPa) levels indicate better heating profiles associated with these modes. For CFSv2 as well, the circulation patterns at the 200-hPa level appear consistent with the 850-hPa pattern, in terms of baroclinicity. However, like at the 850-hPa level, the simulated winds are weaker and the circulation patterns lack organization. Overall, the convection and circulation patterns associated with the different CCEW modes (in their peak phase) are simulated significantly better in CFSsmcm than in CFSv2 climate.

c. MISO

The Indian summer monsoon (ISM) intraseasonal oscillations (ISO) constitute a major component of the tropical climate variability. Like the MJO, the state-of-the-art climate models find it difficult to simulate MISOs as well (Lin et al. 2008b; Sabeerali et al. 2013). There is still a debate on whether the boreal summer MISO mode is distinct from the eastward-propagating MJO mode apart from the fact that the former is prominent in the boreal summer while the latter is dominant in winter (Lau and Chan 1986; Kikuchi et al. 2012). Nonetheless, the MJO has an equatorially trapped spatial structure, whereas the MISO shows an off-equatorial structure with strong convective activity over the South Asian region. In fact, the challenges of simulating MJO and MISO are similar. It is believed that they are both conditioned by a proper representation of organized convection as in essence they are both a by-product of the latter. In section 3a, we have seen that CFSSmcm has significantly improved the simulation of the MJO compared to the host model.
FIG. 9. Zero-lag composite of the respectively filtered OLR (W m\(^{-2}\)) anomalies (in blue–white–red shading) for the different equatorial waves and the corresponding anomalous 850-hPa circulation pattern (m s\(^{-1}\); gray-scaled streamlines). (left) CFSsmcm simulation, (center) observations, and (right) CFSv2.

(a) CFSsmcm KELVIN  (b) OBS KELVIN  (c) CFSv2 KELVIN
(d) CFSsmcm ER  (e) OBS ER  (f) CFSv2 ER
(g) CFSsmcm EIG  (h) OBS EIG  (i) CFSv2 EIG
(j) CFSsmcm WIG  (k) OBS WIG  (l) CFSv2 WIG
(m) CFSsmcm MRG  (n) OBS MRG  (o) CFSv2 MRG
Moreover, GKPMM17a has shown that the distribution of rainfall has also improved in the CFSsmcm simulation, especially over India.

To investigate the ISM intraseasonal variability, we plot the north–south version of the TWK spectra and the conventional east–west TWK spectra (Fig. 11), but for the boreal summer season [June–September (JJAS)] only. Noteworthy, for the north–south TWK spectra (Figs. 11a,c,e), wavenumber 1 corresponds to 50° of latitude (from 20°S to 30°N). In observations (Fig. 11a),
we notice a northward-propagating mode with time period of about 45 days and centered at wavenumber 1. For comparable time period and wavenumber, a southward component is also noted but with less power.

Comparing the model simulations (CFSsmcm in Fig. 11c and CFSv2 in Fig. 11e) with observations, we can see that both models capture the northward- and southward-propagating components but with a longer time period of about 60 days, though the CFSsmcm signal seems to extend to higher frequencies. Also, the power in the MISO modes is slightly underestimated, more so in CFSsmcm simulations. In the east–west TWK spectra (Fig. 11b), the dominant power, seen around wavenumbers 1–2 and time period of 45 days, corresponds to the eastward-moving ISOs or MJOs. The power in the 45-day time period in both the north–south and east–west spectra is consistent with the fact that MISOs predominantly propagate northeastward (Lau and Chan 1986; Goswami 2012). Eastward-moving Kelvin waves and westward ER waves are also seen in the spectra (Fig. 11b). Power in the 10–20-day range propagating westward indicates 10–20-day high-frequency ISOs (Goswami 2012). In the two model simulations, CFSsmcm simulated east–west spectra (Fig. 11b) look more realistic than that of CFSv2 (Fig. 11f). CFSv2 simulates unrealistic eastward power at higher wavenumbers. Also, it simulates spurious power all along the positive wavenumber axis. The westward ER wave power is overestimated by CFSv2, and it peaks at a much longer period of ~60 days. Also, it simulates a weak power for the Kelvin waves, which is consistent with Fig. 1b, and the 10–20-day westward ISO power is underestimated.

The eastward power at 60 days in Fig. 11b is consistent with the power at the same time period in Fig. 11a. This indicates a possibility of realistically simulating the northeastward movement of the monsoon trough by CFSsmcm. Noteworthy, the lack of a strong eastward
power at wavenumber 1 (Fig. 11f), to be associated with the northward-propagation power (Fig. 11c), is unrealistic and raises suspicion about the physical mechanisms behind the simulated northward propagation. CFSv2 fails to simulate the desired power for the westward-propagating 10–20-day high-frequency monsoon ISOs, and it is slightly overestimated in the CFSsmcm simulations. In the remainder of this section, we analyze the 45-day MISO or simply the MISO dynamical structure and physical properties as simulated by the two models. To isolate the MISO anomalies, we apply space–time filtering as we have done in sections 3a and 3b. However, we apply the filter only for the boreal summer data. Based in the spectra shown in Fig. 11, we use the filter with the time-period range of 20–100 days and wavenumber range from 0 to 4. The anomalies isolated for MISO are plotted in Figs. 12–14.

The boreal summer MISO daily OLR variance is plotted in Figs. 12a–c for CFSsmcm, observations (NOAA OLR data), and CFSv2, respectively. In observations (Fig. 12b),
FIG. 13. Latitude–height cross section (averaged for 70°–90°E) of MISO composite of (a)–(c) the MISO-filtered OLR anomalies and the corresponding anomalous (d)–(f) zonal wind (m s\(^{-1}\)), (g)–(i) convergence (s\(^{-1}\)), (j)–(l) relative humidity (%), (m)–(o) temperature (K), (p)–(r) vertical velocity (Pa s\(^{-1}\)), and (s)–(u) diabatic heating rate (K day\(^{-1}\)). (left) CFSsmcm simulation, (center) observations (NOAA OLR), and (right) CFSv2.
the maximum variance is located in the northern Indian Ocean and west Pacific, with the peak at the head of the Bay of Bengal and the high-variance contours displaying a northwest–southeast orientation. Noteworthy, all the high-variance zones are over the oceanic regions in both models and observations. The tilted orientation of the variance pattern is missing in both model simulations (CFSsmcm in Fig. 12a and CFSv2 in Fig. 12c). CFSsmcm fails to capture the peak in the head of the Bay of Bengal region. It is shifted over the Arabian Sea, instead. In fact, the whole CFSsmcm MISO variance, over the west Pacific, is shifted eastward, and it is slightly overestimated. This eastward variance shifting is symptomatic, and it is utterly consistent with that of the MJO and CCEWs in Figs. 2 and 7. It will not be surprising if the ocean model is the culprit, and a thorough investigation of this matter is warranted.

CFSv2 simulates an overestimated peak at the head of the Bay of Bengal and also highly overestimates the variance over the west Pacific. This is consistent with the work of Goswami et al. (2014, 2015), who showed that CFSv2 tends to overestimate the low-frequency ISV. As per the variance plots, both models have difficulties in simulating the daily variance of the MISO though the CFSsmcm simulation has noticeable improvements. The most significant improvements include an extended power over continental India as in the observations and a significant reduction of the faulty power over the western Pacific and the Bay of Bengal.

The northward-propagation feature of MISO is examined by plotting meridional Hovmöller diagrams, averaged over 70°–90°E, of a composite of the MISO-filtered OLR anomalies. The composite is constructed based on an index located over the Bay of Bengal. In observations (Fig. 12e), the MISOs start migrating approximately from 10°S and go up to 25°N with a phase speed of about 1.5° latitude per day. CFSsmcm (Fig. 12d)
captures this phase speed realistically, and the convective
starts migrating from about 10°S as in the observations. The amplitude, however, is weaker, CFSv2
simulated MISOs (Fig. 12f) also appear to be weaker than the observations, but they also have a slower
northward propagation, and the migration starts right at the equator, unlike in the observations and in CFSsmcm.
Circulation pattern south of 10°S looks spurious in the CFSv2 simulation.

The composite circulation patterns for the peak MISO
phase at 850 hPa superposed on the corresponding OLR
anomalies are shown in Figs. 12g–i for CFSsmcm, ob-
servations (OLR from NOAA and winds from NCEP),
and CFSv2, respectively. In the observations (Fig. 12h), a
monsoon troughlike organization is evident in the OLR
anomalies. This is accompanied by a Rossby gyre-type
pair of cyclonic circulations at 850 hPa with a fetch of
easterlies emanating from the northern Pacific Ocean
blowing over India and strong westerlies over the Indian
Ocean. These features are similar to what we had ob-
served in the circulation patterns for the MJO peak
phase shown in Fig. 5b, at least for the Rossby gyres and
equatorial westerlies somewhat lagging the convection
core. A third gyre can be seen in northeastern India.

The CFSsmcm (Fig. 12g) simulated OLR anomalies
rather appear to have a “bloblike” structure instead of a
monsoon troughlike orientation in the sense that it is not
extended in the northwestward direction. However, it
captures the cyclonic circulation slightly north of the
convection maximum reasonably well, but it under-
estimates the one to the south; it is somewhat shifted
to the west, allowing the northwesterly winds to pene-
trate into the Arabian Sea. This is perhaps connected
with the lack of elongation of the OLR signal. The
easterlies over the Pacific are captured reasonably well,
but they look wobbly. The third gyre is shifted northeast.
Again, these biases are somewhat similar to the issues
discussed while describing the CFSsmcm simulated cir-
culation pattern for the peak MJO phase (Fig. 5a).

In the CFSv2 simulation (Fig. 12i), the peak of the
OLR anomalies are heavily shifted eastward compared to
the observations. Moreover, the simulated monsoon
troughlike OLR anomaly pattern has an overestimated
meridionally oriented component extending to 30°S.
Nevertheless, the CFSv2 simulated circulation pattern
look reasonably simulated and somewhat better than
CFSsmcm (cf. Figs. 12g and 12i) except for the fact that
the southern tail of the whole pattern is shifted to
the west.

The winds over the west Pacific are observed to be
dominantly westerlies at 200 hPa. Comparing the
observed winds at 850 and 200 hPa, we note that
the circulations are neither dominantly baroclinic nor
barotropic. This is a feature of the MISO that is different
from MJO, which is dominantly baroclinic (Figs. 5b,e).
This in fact makes the MISOs a dynamically complex
component of the tropical climate and a difficult feature
for the climate models to simulate. CFSsmcm simulates
the 200-hPa circulation patterns for the peak MISO
phase with considerable fidelity. However, the cyclonic
circulation northwest of the convection maximum looks
unrealistic. Nevertheless, comparing the 200-hPa circu-
lation relative to the 850-hPa winds in the CFSsmcm
simulations, the model seems to capture the baroclinic–
barotropic nature of the MISO circulation reasonably
well. CFSv2 simulated winds at 200 hPa (Fig. 12i) show
limited ability in simulating the major observed features.
The fact that CFSv2 simulates a “too much” meridional
orientation of the convective band by simulating the
850-hPa circulation with considerable success while
missing the major circulation features at the 200-hPa
level suggests the possibility of an unrealistic dynamics
in the model.

In Fig. 13, the vertical structure of the MISO mode
is examined. This figure is similar to Fig. 6, but for
MISO. The panels in Fig. 13 show the height–latitude
cross sections of different fields averaged over
70°S–90°E. The top panels show the meridional varia-
tion of the corresponding OLR with the minimum
indicating the peak convection. In observations, the
convection peak is seen at around 7°N (Fig. 13b).
The impression of the cross-equatorial southwesterly
ISM low-level jet is seen in Fig. 13e, where the zero
(meridional) shear line is slightly north (10°N) of the
convection maximum. Around the same location, a
“convergence below and divergence aloft” feature is
seen in Fig. 13h. Positive moisture anomalies with a
significant southward tilt dominate the atmosphere
south of 17°N and negative anomalies northward
beyond 17°N (Fig. 13k). At about 10°N, negative
temperature anomalies are seen at the lower tropo-
sphere (below 600 hPa) and positive anomalies aloft
(Fig. 13n). Updrafts throughout the atmospheric col-
umn are collocated with the convection maximum
(Fig. 13q). The updraft maximum is led by a down-
draft northward and followed (from the south) by a
region of mild updraft in the midtroposphere and
downdraft in the lower and upper troposphere. The
diabatic heating shows positive anomalies collocated
with the convection peak, the maximum heating being
at 400–500 hPa (Fig. 13t). The positive anomalies
are led by negative anomalies northward and followed
by mild positive anomalies in the midtroposphere.
The observational features noted above are consistent
with the shear vorticity–driven northward-propagation
mechanism of MISOs (Jiang et al. 2004).
CFSsmcm reasonably captures the major features, as noted in the OLR meridional profile, zonal wind, convergence, and temperature anomalies (Figs. 13a,d,g,m). The only major concerns of the CFSsmcm simulation are the dry moisture bias immediately south of the equator at about 5°S (Fig. 13j) and the very narrow and highly overestimated values of updrafts (Fig. 13p) and diabatic heating rates (Fig. 13s). In the CFSv2 simulation (Fig. 13, right column), all the fields are found to have major biases. The biases in the zonal wind, convergence, and moisture fields are particularly grave in the backdrop of the fact that CFSv2 simulates reasonable northward-propagating MISOs. The lack of barotropic shear vorticity line and the northward tilt of the moisture anomalies are particularly disturbing. It seems like CFSv2 captures the northward propagation of MISO for the wrong reasons.

To explore the simulation of the observed mechanism of the northward propagation of the MISOs (Jiang et al. 2004) in the two model simulations, we plotted the composite phase-wise latitude–height cross sections (averaged over 70°–90°E) of diabatic heating superimposed on the moisture anomalies in Fig. 14. The observations are shown in the middle column. The red contours show the heating associated with the MISO convection, which starts over the equator and propagates poleward until 20°N. The heating shows a top-heavy vertical structure with the peak heating observed around the 400–500-hPa level attaining a maximum value of 2 K day\(^{-1}\) in phases lags 0 and +5. The associated specific humidity field, shown in shading, indicates a bottom-heavy profile with positive moisture anomalies leading the heating maximum in the lower troposphere synchronous with moisture preconditioning ahead of the convection (indicated by the heating contours) driving the convection northward. Both the heating and moisture fields exhibit a north–south vertical tilt, leaning backward at the upper troposphere.

The CFSsmcm simulation (in the left column) captures this tilted structure reasonably well in both the heating and moisture fields despite a few discrepancies, such as an overestimation of the heating maximum, an earlier peak, and a limited poleward extension. Nevertheless, the moisture preconditioning ahead of the convection maximum is captured well. This preconditioning feature is missing in the CFSv2 simulation (right column). The positive and negative heating contours are in phase with the positive and negative shadings of specific humidity, respectively. Arguably, the tilted vertical structure is backward (and more prominent in the negative heating contours) compared to the observations.

The heating is overestimated in the CFSv2 simulation as in the CFSsmcm simulation; however, in CFSv2, the poleward propagation is observed to reach 20°N like the observations. However, the moisture and heating maxima are in phase, and CFSv2 seems to lack the main moisture preconditioning mechanism, which raises the same questions as the MJO. In the absence of the preconditioning mechanism, what is the mechanism responsible for the northward propagation of the MISOs in the CFSv2 simulated climate? Noteworthy, the CFSsmcm simulated MISO northward-propagation mechanism appears to be consistent with the hypothesis of Jiang et al. (2004), and it is realistic. The realistic simulation of the moisture preconditioning in CFSsmcm climate is undoubtedly related to the prescribed cloud-type trilogy in the SMCM formulation and its ability to simulate the other TISV modes.

4. Discussion

A 15-yr simulation with NCEP’s coupled climate model CFSv2, in which a new SMCM cumulus scheme was implemented (GKPM17a; GKPM17b), CFSsmcm, was analyzed here against a control simulation of the same length and same initial conditions in terms of its ability to capture the main modes of tropical variability on synoptic and intraseasonal scales, including the MJO, CCEWs, and MISOs. NOAA OLR (Liebmann and Smith 1996) and NCEP reanalysis fields (Kalnay et al. 1996) are utilized as an observational benchmark.

a. Physical characteristics of SMCM

SMCM aims to capture the statistics of the subgrid variability of the three cloud types, cumulus congestus, deep, and stratiform (KBM10; Frenkel et al. 2012; Peters et al. 2013; De La Chevrotière et al. 2015), that are observed to characterize multiscale tropical convective systems, including the MJO and CCEWs (e.g., Johnson et al. 1999; Mapes et al. 2006; KM06). As such, CFSsmcm captures most of the spectrum of tropical intraseasonal variability with good fidelity, including many of their physical and dynamical features, while the control model performed very poorly overall. Though there is still room for further improvements, the performance of CFSsmcm is somehow expected based on the previous successes of the SMCM in the context of an aquaplanet atmospheric GCM (Khouider et al. 2011; Ajayamohan et al. 2013, 2014, 2016; Deng et al. 2015, 2016) and the fact that the SMCM is rooted from the thoroughly documented theoretical framework of the multicloud model for convectively coupled waves (KM06; Khouider and Majda 2007, 2008a,b; Han and Khouider 2010).

Instead of carrying an ensemble of convecting plumes to characterize the convective tendencies as in a mass flux CP, the SMCM relies on judiciously chosen vertical
profiles of heating/cooling and drying/moistening. A similar approach has been successfully used by Moncrieff et al. (2017) to design a parameterization for convective momentum transport (CMT) due to mesoscale convective systems. While the parameterization of CMT is not included in the present model, the Moncrieff et al. (2017) strategy can be naturally extended into the CFSsmcm framework.

b. Improved MJO and CCEWs

The first striking improvement is seen in terms of the Takayabu–Wheeler–Kiladis diagram (Takayabu 1994; Wheeler and Kiladis 1999) in Fig. 1. While the control run, CFSv2, has a limited skill in this regard, CFSsmcm shows significant improvements essentially by adding power to the Kelvin, MRG, WIG, and EIG waves, most of which are weaker or inexistent in the control run. The MJO frequency is also improved. Nonetheless, the superiority of the CFSsmcm simulation is more appreciated when digging deeper and looking at the physical and dynamical features of these waves.

The physics and dynamics of the MJO are presented in section 3a. In terms of the geographical distribution of MJO variance, while both simulations exhibit a fair amount of power over the bulk area of the tropical warm pool, they both show some limitations when compared to NOAA OLR. While CFSsmcm suffers from a severe westward shift of the variance maximum, the control run exhibits an unrealistic double peak, each of which are located on either side of the equator, somewhat reminiscent of the double ITCZ problem.

One of the most visible striking outperformance of CFSsmcm comes in terms of the propagation of MJO-filtered OLR composites in Fig. 3. While CFSsmcm shows a clear propagating blob of low OLR, with the right phase speed and geographical location and amplitude as in the observation, CFSv2 fails miserably in this regard. The same consistent behavior is seen in the Hovmöller plots in Fig. 4. Also the famous quadruple vortex structure and associated baroclinicity of the MJO (Rui and Wang 1990; Hendon and Salby 1994; Majda and Biello 2003; Kiladis et al. 2005; Zhang 2005; Majda and Stechmann 2009b) are reasonably captured by CFSsmcm, while the horizontal flow structure of CFSv2 is completely disorganized.

The vertical structure in Fig. 6 raises the question whether the MJO power spectrum peak exhibited by the CFSv2 simulation in Fig. 1 has anything in common with the MJO as a physical mode of tropical variability. CFSv2 lacks the most fundamental dynamical and morphological features such as the absence of a pronounced OLR minimum or any of the fundamental characteristics of the dynamical fields, while CFSsmcm compares relatively well to the observations in all aspects, including the backward tilt in moisture, horizontal wind, and temperature (e.g., Kiladis et al. 2005). In particular, the persistence of low-level moistening and congestus (low level) heating, during the suppressed phase of the MJO for about 2–3 weeks (60°–80° divided by 5 m s⁻¹) prior to the MJO active convection, which is observed in both the CFSsmcm simulation and the reanalysis MJO plots but absent in the control CFSv2 MJO, as illustrated in Fig. 6, is consistent with the idea that congestus heating serves to moisten the environment prior to deep convection as demonstrated by insitu observation from the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)/DYNAMO observation campaign (Johnson and Ciesielski 2013; Bellenger et al. 2015; Chen et al. 2015) and detailed numerical and theoretical studies (Derbyshire et al. 2004; Waite and Khouider 2010; Hohenegger and Stevens 2013; Hirons et al. 2013).

The faithful representation of the MJO’s main physical and dynamical features in the CFSsmcm simulation stems from the design principles of the stochastic multicloud model based on the self-similar morphology and dynamics of multiscale tropical convective systems (KM06; KBM10) and is consistent with previous studies using the deterministic and stochastic multicloud model (Khouider et al. 2011; Ajayamohan et al. 2013, 2014, 2016; Deng et al. 2015, 2016). The superiority of the stochastic simulation, as opposed to global simulations using the deterministic MCM, comes from the fact that the stochastic model is able to simultaneously put variability at a wide range of scales, ranging from mesoscales to planetary scales in an intermittent fashion (Frenkel et al. 2012, 2013; Deng et al. 2016), although the main linear instabilities for the considered parameter regimes, exhibited by the (deterministic) multicloud model, occur at synoptic scales (KM06; Khouider and Majda 2008a,b; Han and Khouider 2010; Khouider et al. 2012).

The simulation of Kelvin waves has always been found to be good in the CFSsmcm simulation even during the tuning of the model (Goswami et al. 2017a). We presume that these improvements in the CCEWs come by virtue of a better simulation of the convective heating profiles, which take into account the proper dynamical interactions of the three cloud types with the large-scale moisture and other thermodynamical fields. Although currently, we do not have solid evidence to support this claim, the improvements in the associated circulation patterns, shown in Figs. 9 and 10, back this well, consistent with the design principle of the multicloud model (KM06; Khouider and Majda 2008a,b; Han and Khouider 2010; Khouider et al. 2011, 2012).
Except for equatorial Rossby waves, CFSv2 shows very little to no power in terms of the distribution of OLR variance of CCEWs as shown in Fig. 7 while CFSsmcm performs relatively well in this regard. However, there are some visible discrepancies when comparing CFSsmcm to the observations, including a westward shift of the maximum variance, particularly for the Kelvin and EIG waves, and differences in amplitude. The westward variance shift is consistent with that of the MJO, and it will not be surprising if they have the same common origin. Curiously, these are all eastward-moving signals. The propagation characteristics and horizontal structures of these waves are equally well captured by the CFSsmcm simulation according to Figs. 8–10. It has to be noted at this point that these are T126 simulations and some features of these waves (such as their convective cores) are represented by less than five grid points in one horizontal direction. CFSv2 does a good job in representing the structure and propagation of the equatorial Rossby waves consistent with the spectral power plot in Fig. 1.

c. Indian summer monsoon ISO and plausible mechanism of northward propagation

Last but not least, the capability of CFSsmcm to capture the physical and dynamical features of the Indian summer MISO is assessed in section 3c and Figs. 11–14. First, from Fig. 12, the distribution of the MISO-filtered OLR variance is captured relatively well compared to the control run that puts too much power over the western Pacific and the Bay of Bengal. Also, the northward propagation over the Indian Ocean and continental India, which appears to be too slow and has a too-weak amplitude and small migrating right at the equator instead of 10°S, in the CFSv2 control run, is considerably corrected in the CFSsmcm run. There is significant evidence that it is the low-level moisture convergence north of the convection maximum that drives the convection northward. Jiang et al. (2004) argued that a heat source, in the presence of an easterly mean flow, leads to a cyclonic barotropic vorticity centered slightly to the north of the heat source, which in turn drives the frictional convergence in the boundary layer, consistent with the finding of De La Chevrotière and Khouider (2017), who coupled the SMCM to an idealized three-layer zonally symmetric model monsoonlike simulation. In a recent study, Hazra and Krishnamurthy (2015) argued that moisture anomalies may provide the necessary preconditioning to promote the northward propagation of MISOs, a mechanism analogous to the preconditioning mechanism in the case of MJOs (Jiang et al. 2011; Khouider et al. 2011). Abhik et al. (2013) also argue in favor of a preconditioning mechanism for northward propagation of the MISOs.

By the SMCM design, the congestus cloud types heat the lower troposphere and cool the upper troposphere, and as such, they trigger low-level (second baroclinic mode) convergence of moisture, which preconditions the environment for deep convection. KM06 took this one step further by showing that when the second baroclinic moisture convergence is turned off, the main linear instability of synoptic-scale moist gravity waves, a surrogate for Kelvin waves in that 2D setting without rotation, disappears. Cumulus congestus clouds can in reality also precondition the environment through the reevaporation of detrained cloud water at their top (Waite and Khouider 2010; Frenkel et al. 2013). However, this effect is arguably ineffective at the MJO scale (Hohenegger and Stevens 2013), though it may play an important role during the initiation phase (Johnson and Ciesielski 2013; Ruppert and Johnson 2015; Bellenger et al. 2015; Hagos et al. 2014; Takemi 2015).

We explored the preconditioning mechanism for the northward propagation of the MISOs in Figs. 13 and 14. The vertical structure of this mode is well captured by CFSsmcm, compared to observations as shown in Fig. 13, hinting to the shear vorticity–moisture preconditioning mechanism (Jiang et al. 2004; Abhik et al. 2013; Hazra and Krishnamurthy 2015) being at work. However, the CFSv2 MISO signal has too little in common with this mechanism. Arguably, the northward-propagating ISO in CFSv2 obeys completely different physics than what actually occurs in nature, and the same can be said about its MJO.

5. Conclusions

The fact that CFSsmcm captures the physical and dynamical features of the main tropical modes of variability is not a matter of serendipity but can be rooted to the theoretical foundation laid by the work of Khouider and Majda (2006, 2008b) and KBM10, guided by observations (Lin and Johnson 1996; Johnson et al. 1999). This is also due to the empirical evidence of the SMCM’s ability to realistically capture the stochastic behavior of tropical convection (Peters et al. 2013) and to the fact that a significant set of parameters (viz., the transition time scales) used here were obtained via a systematic Bayesian inference method (De La Chevrotière et al. 2015) based on large-eddy simulation data (Khairoutdinov et al. 2009).

The results shown here are yet another demonstration that tropical convective variability is both multiscale and self-similar in nature and most of it can be explained by the complex interactions of the three key cloud types,
congestus, deep, and stratiform, with the dynamical and moisture fields, by shaping up the vertical structure of the diabatic heating, on multiple time and spatial scales. The improvement shown by the CFSsmcm model in simulating the tropical intraseasonal variability promises to improve the seasonal to subseasonal (S2S) predictability of the simulated climate as well. The S2S skill of the CFSsmcm is currently under investigation and will be reported elsewhere by the authors.

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