Intraseasonal, Seasonal, and Interannual Characteristics of Regional Monsoon Simulations in CESM2

Gerald A. Meehl1,2, Christine Shields1, Julie M. Arblaster1,2, H. Annamalai3, and Rich Neale1

1National Center for Atmospheric Research, Boulder, CO, USA, 2ARC Centre of Excellence for Climate Extremes, Monash University, Melbourne, Victoria, Australia, 3IPRC/Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI, USA

Abstract A survey of intraseasonal, seasonal, and interannual precipitation and 850 hPa winds for various monsoon regimes around the world is presented for the Community Earth System Model Version 2 (CESM2) compared to observations and the previous generation CESM1. In CESM2 the south Asian monsoon has a reduction of excessive precipitation in the western Indian Ocean and an increase of precipitation in the eastern Bay of Bengal and land areas of Vietnam, Cambodia, and Laos. The seasonal timing of the south Asian monsoon, monsoon-ENSO connections, and monsoon intraseasonal variability all are improved compared to CESM1. For the Australian monsoon, deficient precipitation over the Maritime Continent has been improved in CESM2 with increases of precipitation over the large tropical islands of Borneo, Celebes, and Papua New Guinea and decreases over southwestern Australia. In the West African monsoon, May–June seasonal rainfall occurs more preferentially over the African coast in CESM2 as in observations, and excessive rainfall over the Ethiopian region is reduced. During July–September in the West African monsoon, deficient precipitation over equatorial Africa in CESM1 has been lessened in CESM2, and there are increases in precipitation over the Guinean coast, though there is little overall improvement in the South American monsoon. In the South American monsoon, precipitation in CESM2 is improved with increased precipitation over the Amazon in central and western Brazil. CESM2 simulates a reduction of excessive precipitation seen in CESM1 over coastal Mexico extending up into the U.S. Great Plains in the North American monsoon.

Plain Language Summary A survey of simulations of regional precipitation and 850 hPa winds is presented for the Community Earth System Model Version 2 (CESM2) compared to observations and the previous generation CESM1 for the south Asian and Australian monsoons, the West African and South American monsoons, the North American monsoon, and the South American monsoon. There are mostly improvements in the seasonal timing, monsoon-ENSO connections, distribution of seasonal mean rainfall, and intraseasonal variability in CESM2 compared to CESM1 in the monsoon regimes.

1. Introduction

As part of the ongoing model development and improvement process for the Community Earth System Model (CESM), the monsoon simulations in successive generations of models have been evaluated (Cook et al., 2012; Meehl et al., 2006; Meehl et al., 2012; Shields et al., 2016). Though there has been a steady improvement in many aspects of the monsoon simulations, a number of systematic errors remain to be addressed. The purpose of this paper is to describe intraseasonal, seasonal, and interannual precipitation and low-level wind features of the monsoon simulations in major monsoon regimes around the world in the latest version of CESM, the CESM2 (Danabasoglu et al., 2020) in comparison to the previous generation model, the CESM1, and to observations.

Section 2 addresses the CESM1 and CESM2 model versions and observations used in the paper, section 3 shows results for the south Asian monsoon, and section 4 follows with a description of monsoon-ENSO connections. Section 5 presents results for the Australian monsoon, with section 6 providing a synthesis of the Asian-Australian monsoon system and section 7 showing results for intraseasonal variability associated with the Asian-Australian monsoon. Sections 8 and 9 show results for the monsoons of Africa (West African and...
South African, respectively), while sections 10 and 11 describe the simulations of the South and North American monsoons, respectively. Section 12 follows with discussion and conclusions.

2. Models and Observations

The components and coupled simulations of CESM1 were described by Hurrell et al. (2013), for CESM1.1 by Kay et al. (2015), and for CESM1.3 by Meehl et al. (2019). The atmospheric model in CESM1 had a nominal 1° latitude-longitude resolution, as did the ocean with enhanced resolution in the latter near the equatorial waveguide. The CESM2 has had a number of improvements and modifications from the versions of CESM1 (Danabasoglu et al., 2020). In the atmosphere, the resolution is the same; however, a number of features that directly affect monsoon regimes involving the boundary layer, convection scheme, and precipitation processes have been improved. The separate representations of the boundary layer, shallow convection, and large-scale condensation (e.g., the boundary layer in the University of Washington, UW, scheme and Park scheme for shallow convection and macrophysics in CESM1) have been replaced by the Clouds Unified By Binormals (CLUBB; Golaz et al., 2002). CLUBB is a high order turbulence closure scheme and uses simple PDFs to describe the subgrid scale distributions of key humidity, saturation, temperature, and vertical velocity quantities. The previous version of the Morrison Gettelman (MG1) microphysics scheme in CESM1 has been updated to MG2 in CESM2 that now predicts rather than diagnoses precipitating hydrometeors (Gettelman & Morrison, 2015). Direct modifications to the Zhang-McFarlane deep convection scheme (Neale et al., 2008; Zhang & Mcfarlane, 1995) act to further increase humidity sensitivity, and the near-surface stress scheme of Beljaars et al. (2004) acts to reduce excessive drag seen in CESM1. The final major change is to advance the modal aerosol scheme from three to four modes (MAM4, Liu et al., 2016), which includes an improved aging process for black carbon.

The ocean model in CESM2 is a version of PoP used in CESM1 but with many improvements to the physics (Danabasoglu et al., 2020). The sum total of these improvements in the ocean model, along with those in the atmospheric model, have produced generally warmer tropical SSTs and reduced the cool bias seen in the equatorial Pacific in CESM1 as noted in Danabasoglu et al. (2020). These warmer tropical SSTs, including the zonal extent of the cold tongue bias (Capotondi et al., 2020), have, in most cases, contributed to improved monsoon simulations as discussed below. The ocean has a nominal 1° horizontal resolution and enhanced resolution in the equatorial tropics, and 60 levels in the vertical with ocean biogeochemistry. Other features of CESM2 involving land and sea ice are described in detail by Danabasoglu et al. (2020).

Observations used here include TRMM/ERA-I gridded precipitation (Huffman et al., 2007), and ERA-I 850 hPa winds and sea surface temperatures (SSTs) (Dee et al., 2014). Further documentation of observational data sources is described in the Model and Data Availability section near the end of the paper.

3. The South Asian Monsoon

Seasonal mean precipitation (June–September, JJAS) for CESM1 and CESM2, observations (TRMM/ERA-I), the difference CESM2 minus CESM1, and respective differences of the model simulations from observations are shown in Figure 1. A persistent systematic error that has been present in previous versions of CESM and in other Earth system models as well (e.g., Annamalai et al., 2017; Sperber et al., 2013) is precipitation maxima that extend too far west in the western Indian Ocean, as seen in CESM1 (Figure 1b) compared to observations (Figures 1c and 1f). This systematic error has been reduced somewhat in the CESM2. Tracking the position of the 6 mm day$^{-1}$ contour in observations near the equator, it lies at about 60°E (Figure 1c). In CESM1 it was around 50°E (Figure 1b), and in CESM2 it is farther east and closer to the observed location of about 60°E (Figure 1a). This movement of the western Indian Ocean precipitation maximum to the east in CESM2 in closer agreement with observations shows up as large negative differences in Figure 1d of about $-6$ mm day$^{-1}$, with the large significant positive precipitation anomaly of 6 mm day$^{-1}$ in CESM1 compared to observations in the western Indian Ocean (Figure 1f) reduced by about a third to roughly $+2$ mm day$^{-1}$ in CESM2 (Figure 1e), thus signaling improvement of this aspect of the seasonal monsoon pattern. However, the precipitation maximum near 5°S seen in observations (Figure 1c) with overly strong amplitude in CESM1 (Figures 1b and 1f) has shrunk in CESM2 (Figure 1a) with consequent significant negative precipitation deficits of about $-5$ mm day$^{-1}$ near 5°S (Figure 1e). Therefore, some
improvement in the westward extent of the precipitation maxima in the western Indian Ocean in CESM2 is accompanied by a reduction of the precipitation maximum at 5°S.

Another flaw in the seasonal mean precipitation pattern in CESM1 was the virtual absence of the precipitation maximum in the eastern Bay of Bengal and the coasts of Myanmar and Thailand, with hardly any
rainfall occurring over land areas of Vietnam, Cambodia, and Laos (cf. CESM1 in Figure 1b to observations in Figure 1c). Consequently, there are significant negative precipitation differences for CESM1 minus observations of around −6 mm day\(^{-1}\) in those regions (Figure 1f). However, CESM2 is considerably improved in these aspects with a quite strong precipitation maximum in that region (Figure 1a) compared to observations (Figure 1c) and represented by large significant positive precipitation differences of up to +6 mm day\(^{-1}\) in the western Bay of Bengal and over Indochina for CESM2 minus CESM1 (Figure 1d). The increase of precipitation over land in CESM2, in closer agreement with observations here and in other monsoon regimes, is likely related to a response to the MG2 rain production (prognostic) versus MG1 (diagnostic). In terms of the magnitude it seems the increased humidity sensitivity in the deep convection is partly responsible, in addition to CLBB in CESM2 versus UW in CESM1, which also smooths out the precipitation in the Bay of Bengal (UW). Even with these improvements in CESM2, there is still deficient rainfall of around −3 mm day\(^{-1}\) over northern India and the Bay of Bengal compared to observations (Figure 1e).

Another systematic error present in CESM1 that has been improved in CESM2 is that monsoon precipitation in CESM1 that extended too far to the northwest over Pakistan now is more contained to the southeast in closer agreement with observations (Figures 1a–1c). This is evidenced by significant negative precipitation differences over northwest Pakistan of about −3 mm day\(^{-1}\) for CESM2 minus CESM1 (Figure 1d), and negative anomalies of less than approximately −1 mm day\(^{-1}\) for CESM2 minus observations (Figure 1e). The relative decrease of precipitation over northwest India in CESM2 compared to CESM1 has contributions from excessive northerlies over Afghanistan and Iran and their penetration and curvature to the east over Arabia.

In summary, compared to CESM1, in CESM2 we note a redistribution of seasonal mean precipitation, improving it in some regions (western Indian Ocean and land areas of Southeast Asia) while deteriorating in other regions (near 5°S in the Indian Ocean). This is very typical of state-of-the-art coupled models and clearly implicates the interactive and intertwined processes that make up the regional monsoon precipitation climatology over South Asia (e.g., Annamalai et al., 2019).

### Table 1

<table>
<thead>
<tr>
<th>Monsoon region</th>
<th>Cases</th>
<th>Pearson pattern correlation</th>
<th>RMSE (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Asian</td>
<td>CESM2 vs. CESM1</td>
<td>.93</td>
<td>2.52</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.88</td>
<td>2.60</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.84</td>
<td>3.09</td>
</tr>
<tr>
<td>Australian</td>
<td>CESM2 vs. CESM1</td>
<td>.92</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.87</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.86</td>
<td>2.28</td>
</tr>
<tr>
<td>W. African—MJ</td>
<td>CESM2 vs. CESM1</td>
<td>.92</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.82</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.74</td>
<td>1.96</td>
</tr>
<tr>
<td>W. African—JAS</td>
<td>CESM2 vs. CESM1</td>
<td>.93</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.88</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.85</td>
<td>1.33</td>
</tr>
<tr>
<td>S. African</td>
<td>CESM2 vs. CESM1</td>
<td>.92</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.87</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.86</td>
<td>1.45</td>
</tr>
<tr>
<td>S. American</td>
<td>CESM2 vs. CESM1</td>
<td>.92</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>4CESM2 vs. TRMM</td>
<td>.88</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.86</td>
<td>2.24</td>
</tr>
<tr>
<td>N. American</td>
<td>CESM2 vs. CESM1</td>
<td>.92</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>CESM2 vs. TRMM</td>
<td>.87</td>
<td>.96</td>
</tr>
<tr>
<td></td>
<td>CESM1 vs. TRMM</td>
<td>.83</td>
<td>1.01</td>
</tr>
</tbody>
</table>

*Note.* The West African monsoon statistics are shown for both MJ (May–June) and JAS (July–September).
The major features of the 850 hPa wind field are captured relatively well in CESM2, as they were in CESM1 compared to observations, with strong cross-equatorial flow in the western Indian Ocean, and westerlies carrying right across the Indian subcontinent and on to Indochina (Figures 1a–1c). Winds over the Bay of Bengal in CESM2 are stronger by about 20% compared to CESM1 and in closer agreement with observations in association with the increased precipitation in the eastern Bay of Bengal and Indochina. Simulating the wind patterns has higher skill due to the fact the wind response depends on the integrated diabatic heating and not on the regional details of the simulated precipitation (e.g., Sperber et al., 2013).

These improvements in the south Asian monsoon simulation in CESM2 compared to CESM1 are quantified in Table 1 where the pattern correlation with observations is higher in CESM2 (0.88 compared to 0.84 in CESM1) and CESM2 has a lower root-mean-square error (RMSE) (2.60 compared to 3.09 in CESM1). Thus, there is improvement in the south Asian monsoon simulation in CESM2 even though the overall pattern in the two models is comparable (pattern correlation of 0.93).

The timing of the seasonal monsoon maximum can be as important as the amount of precipitation itself. The lower panels of Figure 1 depict the monthly mean zonal mean precipitation averaged from 70°E to 100°E to show the seasonal cycle. The onset of heavy precipitation (greater than 10 mm day\(^{-1}\)) in the maximum of the monsoon precipitation from 10°N to 25°N occurs in June in both observational data sets and in both models (Figures 1g–1j). However, the models show an anomalous precipitation maximum over the Himalayas near 29°N and also miss the more gradual onset of precipitation amounts greater than about 8 mm day\(^{-1}\) near 10°N in May.

Figure 2 shows a geographical depiction of the monthly timing of the climatological precipitation maximum over the region. On the whole the observed timing peak occurs in July over the Indian subcontinent consistent with the subseasonal time evolution in Figure 1 (a few regions have wintertime peaks associated with the northeast winter monsoon) (Figure 2a). In CESM1 the peak occurs more during August, even into the Bay of Bengal where the observed peak is much earlier in June (Figure 2c). CESM2 broadly improves on this with the peak now occurring during July (Figure 2b). In observations, to the east the observed peak occurs progressively (from June over Bay of Bengal to October over South China Sea), illustrating the eastward extension of the mean monsoon precipitation. In the CESM2, this feature is reasonably simulated (from July to September-October) despite a stronger wet bias over the plains of Indo-China in CESM2 (Figure 1).

The simulation of the 850 hPa wind in CESM1 in Figure 1 indicates a more realistic monsoon trough over the Bay of Bengal than in CESM2 even though the latter has a better precipitation simulation. To gain more insight into this feature, Figure 3 shows vertically integrated vapor transport (IVT) over the south Asian monsoon region from the two models and observations. CESM2 has larger-than-observed values of IVT over the Arabian Sea and Bay of Bengal compared to CESM1, and this contributes to the greater magnitudes of monsoon precipitation noted in Figure 1 in CESM2 compared to CESM1. For example, IVT is about a factor of 2 larger in CESM2 compared to CESM1 and observations over the Bay of Bengal and land areas of Southeast Asia. The larger values of IVT in CESM2 extend farther east over Thailand, Cambodia, and Laos as observed, thus contributing to the improvements of monsoon precipitation seen there in comparison to CESM1 noted in Figure 1. These larger-than-observed values of IVT in CESM2 can be traced in part to the warmer-than-observed SSTs in the tropical Indian Ocean that produce greater evaporation and water vapor
Figure 3. JJAS integrated vapor transport (IVT) for the south Asian monsoon region for (a) CESM2 and (b) CESM1, (c) MERRA2, (all $kg \cdot m^{-1} \cdot s^{-1}$). The 1980–2015 IVT strength is shown in color contours and with the vector components shown as arrows. Maximum vector length corresponds to a value of 600 $kg \cdot m^{-1} \cdot s^{-1}$. IVT was computed by integrating from the surface to 200 hPa. Model data are ensemble means, CESM2 11 members, and CESM1 42 members, 1986–2005; MERRA2 data from 1980–2015 (doi: 10.5065/D62R3QFS).
to be carried across the monsoon domain to Southeast Asia (SST errors will be discussed further in relation to Figure 8 below).

4. Monsoon-ENSO Connections

An important component of any model development is to assess if the model realistically captures the impact of ENSO on the monsoon precipitation and circulation at interannual timescales since extreme droughts and flood conditions over South Asia are determined in large part by ENSO characteristics (e.g., Sikka, 1980; Pillai & Annamalai, 2012). A simple metric for assessing ENSO-monsoon association is to calculate the simultaneous correlation of area-averaged JJAS all-India rainfall (AIR, land points averaged over 7°–30°N, 65°–95°E) with surface temperature for CESM2 and observations (AIR index computed from observed precipitation over India; Figure 4) for the 1950–2010 period. The CESM2 captures the observed opposition of sign between monsoon rainfall and eastern tropical Pacific SSTs, with above normal monsoon rainfall associated with below normal eastern tropical Pacific SSTs and vice versa. Above normal monsoon rainfall also is associated with below normal surface temperatures over the Indian monsoon land regions and in the western Indian Ocean and Arabian Sea due to enhanced cloudiness and rainfall and stronger winds that produce cooler SSTs, respectively. As in previous generations of CESM (e.g., Meehl et al., 2012), the negative correlations in the equatorial eastern Pacific reach too far westward, with the zero line extending nearly to 130°E compared to observations farther east at 160°E. The model correlations are of greater magnitude with larger areas of statistical significance compared to the observations in association with Niño3.4 standard deviations being about 30% stronger than observations in CESM2 (Capotondi et al., 2020). For example, the extent of the −0.5 correlation in the equatorial Pacific in CESM2 extends from about 160°E to 100°W (Figure 3a), while in the observations it ranges from about 170°W to 100°W (Figure 3b). However, maximum values of the negative correlations in the eastern equatorial Pacific are roughly comparable, with values between −0.5 and −0.6 in both the CESM2 and observations.

Meanwhile, the CESM2 simulation of these spatial features of interannual variability is much improved compared to CESM1 (Figure 4b). The overall values of the negative correlations in the eastern equatorial Pacific and over the Indian land areas are reduced in CESM1 by over 50% compared to observations with the strong negative correlations over India and the western Arabian Sea seen in CESM2 and the observations not present in the CESM1 simulation. Both CESM1 and CESM2 show larger-than-observed positive correlations over the Maritime Continent extending poleward into the sub-tropics of both hemispheres. This is likely related to a stronger-than-observed Hadley Circulation in CESM1 (Danabasoglu et al., 2020) and in CESM2 (Simpson et al., 2020).

The strength of the negative correlations between monsoon rainfall and tropical Pacific SSTs relates to the dynamics of the large-scale east-west (Walker) circulation between the Pacific and Indian sectors. Thus, during a composite observed El Niño event, maximum SSTs of nearly 30°C set up near the Dateline during November and December of the year of onset of the event (Year 0; Figure 5c) associated with precipitation values of 10 mm day⁻¹ extending from the Dateline to about 150°W during December of Year 0 to February of Year +1 (Figure 5). These precipitation maxima are preceded by comparable precipitation values near 150°E during February and May of Year 0. For CESM2, somewhat larger SST values of about 31°C set up at about the same time but are about 10° of longitude farther west (Figure 5a), in a similar location to CESM1 (Figure 5b) as those seen in the observations (Figure 5c). With the warmer SSTs in CESM2
compared to CESM1 (Figures 5a and 5b), there are correspondingly larger values of precipitation up to 18 mm day$^{-1}$ in CESM2 but with roughly the same seasonal timing and westward shift in location (Figure 5d) as in the observations (Figure 5f) that were not present in CESM1 (Figure 5e). This is an improvement in CESM2 from CESM1 and previous model versions (Meehl et al., 2012) where the model-simulated the maximum SST and precipitation values were even farther west. Thus, with the improved position and seasonal timing of ENSO SST and precipitation values in CESM2 compared to CESM1, the anomalous Walker Circulation should set up in a comparable location in CESM2 and provide similar magnitude negative correlations between Indian monsoon rainfall as represented by the observed AIR index as noted in Figure 4.

In addition to the well-known relationship between above normal AIR and below normal eastern tropical Pacific SSTs, the magnitude of this correlation is known to fluctuate on interannual to decadal timescales (e.g., Meehl et al., 2012; Parthasarathy et al., 1991), associated in part with decadal modulation of ENSO characteristics (e.g., Annamalai et al., 2007) or aspects of tropical Indian Ocean variability (e.g., Ashok et al., 2001). To examine this relationship as a function of time, a running 13 year correlation is shown in Figure 6 between the JJAS AIR and the JJAS Niño3.4 SSTs. CESM2 better captures the strength of this observed correlation compared to CESM1 and previous model versions shown by Meehl et al. (2012). Correlations in the historical simulations in CESM2 range from about $-0.9$ to $-0.5$ with two occurrences

Figure 5. (a) CESM2 El Niño composites from years across all historical ensemble members, Niño3.4 total sea surface temperature (°C); (b) same as (a) except for CESM1; (c) same as (a) except for HadISST observations (1870–2018); (d) same as (a) for CESM2 except for total precipitation (mm day$^{-1}$); latitudes are averaged between 3°N and 3°S; (e) same as (d) except for CESM1; (f) same as (d) except for GPCP observations (1979–2017). Composites include all years greater than 1 standard deviation for Niño3.4 SST for 11 ensemble members in CESM2 and 42 for CESM1.
of near zero correlation and one occurrence of a positive correlation of about +0.2 (Figure 6b). This
compares favorably with the observations (Figure 6a) with a similar range and one occurrence of a
positive correlation of around +0.2. There were smaller negative correlations in CCSM4 of −0.7 to
−0.2 with numerous occasions of positive correlations nearing +0.2 in the earlier model (Meehl et al.,
2012). These characteristics are also present in CESM1 in Figure 6. Thus, for this quantity, CESM2 is notably
improved compared to CESM1.

Additionally, the magnitude of these correlations could be affected by the amplitude of ENSO and position
of maximum SST and precipitation during ENSO events. As noted above, though the maximum SST and
pre-cipitation values are shifted a bit west during ENSO events in CESM2, these are better simulated than in
CESM1 and CCSM4. The larger values in CESM2 compared to CESM1 and observations provide larger
force of the large-scale divergent circulation and reinforce a strong monsoon-ENSO connection. This quantity
is much improved in CESM2 compared to CESM1, though there could be compensating errors that
produce this improvement (Simpson et al., 2020). With regards to amplitude, CESM2 ENSO is about 30% larg-
er than observed but closer to observations than in CCSM4 or CESM1, with comparable frequency com-
pared to observations (Capotondi et al., 2020; Deser et al., 2012).

In summary, improvements in position of maximum SST and precipitation during ENSO events compared
to earlier model versions, even with somewhat of a westward shift, contribute to an improved upper level

Figure 6. Running 13 year correlations between JJAS all-India rainfall (AIR) and Niño3.4 SSTs for (a) observations;
(b) individual ensemble members from the CESM2 historical simulation, with the ensemble mean in black; and
(c) Years 1–1,200 from the CESM2 preindustrial control run; (d) same as (b) except for CESM1; (e) same as (c) except for
310 years from the CESM1 control.
divergent circulation and the magnitude of the monsoon-ENSO negative correlation that is closer to observations in CESM2 than in CESM1.

5. Australian Monsoon

Two of the major flaws in the simulation of seasonal (December–February, DJF) precipitation in the Australian monsoon in CESM1 were the deficient rainfall over the maritime continent, and excessive precipitation too far to the southwest over Australia (Figure 7b compared to observations in Figure 7c). Both of these deficiencies have been improved in CESM2 (Figure 7a). There are significant increases of precipitation particularly over the large tropical islands of Borneo, Celebes, and Papua New Guinea of around 5 mm day$^{-1}$ and decreases of about that same magnitude over southwestern Australia (Figure 7d). With these improvements has come a decrease in the CESM2 precipitation maxima over northern Australia and the Gulf of Carpentaria with CESM2 values in those regions about 20% less than observations (cf. CESM2 in Figure 7a to observations in Figure 7c). The improvements in CESM2 compared to CESM1 related to observations produce lower amplitude differences from observations over most of the Australian monsoon.

Figure 7. Same as Figure 1 except for the Australian monsoon, DJF; bottom four panels averaged from 120–150°E.
domain (cf. Figures 7e and 7f). These improvements are represented by a slight increase in pattern correlation from 0.86 in CESM1 to 0.87 in CESM2, and, in particular, a reduction in RMSE in CESM2 to 2.19 compared to 2.28 in CESM1 (Table 1).

The monthly mean subseasonal latitudinal evolution of precipitation over the Australian monsoon is also much improved in CESM2 compared to CESM1 as a consequence as shown in Figure 7, bottom. The larger amplitude and farther southward penetration of monsoon precipitation in CESM1 (Figure 7j) have been improved in CESM2 (Figure 7i) though the maximum amplitude of monsoon precipitation near 13°S is reduced by about 15% in CESM2 compared to observations (Figures 7g, and 7h).

In association with these improvements in the regional precipitation distribution, the low-level winds also have improved in CESM2 compared to CESM1, particularly over Australia where there are now well-defined easterlies over most of the country (Figure 7a) as in observations (Figure 7c) compared to northeasterlies in CESM1 (Figure 7b).

6. Factors Affecting the Asian-Australian Monsoon Simulations

It has been speculated that the systematic error for the South Asian monsoon of too much precipitation too far west in the western Indian Ocean could be affected by an overly strong cold tongue in the Pacific and deficient precipitation over the Maritime Continent (e.g., Meehl et al., 2012), or an overly strong Bjerknes' feedback along the equatorial Indian Ocean (Annamalai et al., 2017), or limitations in representing regional air-sea interactions off the Somali-Oman coasts and associated atmospheric boundary-layer processes (Hanf & Annamalai, 2020). Figure 8 shows annual mean SST and surface wind stress for observations, CESM2, CESM1, differences from observations, and the difference, CESM2 minus CESM1 (seasonal means show similar systematic error patterns). In CESM2 (Figure 8b), SSTs in the Western Pacific Warm Pool exceed 30°C and are roughly 1–2°C warmer than in CESM1 (Figures 8c and 8d) and about 1°C warmer than observations (Figures 8a and 8e). This is consistent with about the same increase in magnitude of SSTs near the Dateline in ENSO events (Figure 5). The excessively low SSTs in the eastern Pacific cold tongue in

Figure 8. Annual mean base state surface temperature (°C) and wind stress (N m⁻², scaling arrow at upper right in each panel) for (a) observations (Large & Yeager, 2009; HadSST); (b) CESM2, (c) CESM1, (d) as in (a) except for anomalies computed for CESM2 minus CESM1; (e) as in (d) except for CESM2 minus observations; (f) as in (d) except for CESM1 minus observations.
CESM1 (Figures 8c and 8f) are now closer to observations (Figure 8a) in CESM2 (Figure 8e). Consequently, there are weaker trade winds in the northeastern tropical Pacific in CESM2 compared to CESM1 (southwesterly anomalies in Figure 8d). The reduced double ITCZ in CESM2 (Danabasoglu et al., 2020) is associated with stronger southeast trades in the southeast tropical Pacific (southeasterly anomalies in Figures 8d and 8e) and SSTs in the southeastern tropical Pacific that are cooler in CESM2 compared to CESM1 by about 1°C (Figure 8d). The warmer than observed SSTs over the western Pacific warm pool in CESM2 (Figure 8e) act to increase precipitation over the Maritime Continent in CESM2 and draw the center of gravity for monsoon precipitation farther east and closer to observations (cf. Figures 1 and 7). The reduced zonal extent of the cold tongue bias in CESM2, compared to CESM1, also likely contributes to an improved simulation of monsoon precipitation (Capotondi et al., 2020).

7. Intraseasonal Variability in the Asian-Australian Monsoon

7.1. Northward Propagating Intraseasonal Oscillations in the South Asian Monsoon

Figure 9 for JJAS shows a composite analysis of the coherent intraseasonal propagating events that originate over the tropical central-eastern Indian Ocean during the monsoon and propagate northward through the Bay of Bengal and extend over land. Such a northward propagating precipitating feature is called either the Intraseasonal Oscillation (ISO; e.g., Karmakar & Krishnamurti, 2019), the Monsoon Intraseasonal Oscillation (MISO; e.g., Suhas et al., 2012), or the Boreal Summer Intraseasonal Oscillation (BSISO; Yasunari, 1979). All refer to the same phenomenon (we will use BSISO here) that is the dominant subseasonal mode of the Indian monsoon and lies at the center of the active-break monsoon cycles of the region (e.g., Sikka, 1980). Compared to its northern wintertime counterpart, the Madden Julian Oscillation (MJO, discussed below) in which the convective anomalies are predominant along the equatorial latitudes and have a large influence on Australian monsoon intraseasonal variability (e.g., Madden & Julian 1994; Hung et al., 2013), the BSISO has eastward and poleward propagating components over the tropical Indo-West Pacific regions (e.g. Annamalai & Sperber, 2005). These northward propagating disturbances characterized by the BSISO remain a simulation challenge for climate models (Neena et al., 2016; Sabeerali et al., 2013; Sperber et al., 2013; Sperber & Annamalai, 2008), and yet they are crucial for monsoon prediction within a season (Goswami & Xavier, 2003). CCSM4 (Meehl et al., 2012) and CESM1 (Figure 9c) were similar in that both model versions underestimated both the coherence and northward propagation characteristics of the BSISO. Although the surface zonal winds and precipitation signals are somewhat in quadrature just north of the equator and at around 20°N, there is no propagation connection between the two in CESM1 (Figure 9c). CESM2 represents a significant improvement, exhibiting coherent northward propagating events of precipitation and surface winds north of the equator that are in quadrature (Figure 9b cf. observations in Figure 9a). One degradation, however, is a lack of southward connection from the equatorial region to the southern Indian Ocean compared to observations. It is possible that limitations in simulating this aspect of BSISO relate to the model’s fidelity in representing the basic state (Sperber & Annamalai, 2008). They suggested that there should be a minimum intensity of precipitation over the equatorial Indian
Ocean to force Rossby waves that then appear as part of a poleward migration. There is a clear connection to improvements in BSISO in CESM2 compared to CESM1 from examination of the regional improvements in mean precipitation distribution described earlier (Figure 1). For example, there are precipitation increases in the Bay of Bengal (an improvement) but decreases south of the equator (a degradation) between CESM2 and CESM1. The former likely contribute to the overall improvement in BSISO in CESM2, while the latter could be affecting the lack of connection to the south Indian Ocean.

7.2. Intraseasonal Variability Associated With the MJO in the Australian Monsoon in DJF

The Australian monsoon variability seems to also benefit from improvement in the intraseasonal oscillations, in this case the MJO. The Indo-Pacific region has a very consistent composite eastward propagating signal, with precipitation surface quadrature coherence that extends through the Australian Monsoon region (Figure 10b cf. Figure 10a). In CESM1, any intraseasonal signal is confined entirely to the Indian Ocean, with an erroneous westward propagation (Figure 10c). Thus, the Australian Monsoon region in CESM1 is not subject to any appreciable variability associated with MJO events but has a larger contribution from MJO variability in CESM2. In response to a number of parameterization changes, primarily deep convection (e.g., Bogenschutz et al., 2018, and discussed further below) and because of a different response to the underlying SST distributions, CESM2 supports stronger and more regionally extensive MJO events that are now able to propagate out of the Indian Ocean and into the West Pacific. This, therefore, subjects the Maritime Continent and the Australian monsoon region to a much more realistic level of intraseasonal monsoon variability.

These improvements in eastward propagation of subseasonal variability in CESM2 compared to CESM1 are also seen in the lower panels of Figure 10 that show a similar magnitude and coherent southward propagation of anomalies in CESM2 (Figure 10e) and observations (Figure 10d). In comparison, CESM1 (Figure 10f) has weaker magnitude and less clear southward propagation of anomalies.
8. West African Monsoon

There are two distinct warm-season precipitation regimes over West Africa, namely, the May–June (MJ) period of strong Guinean coast rainfall and the July–September (JAS) period with rainfall in the Sahel (Cook et al., 2012), and we show both periods here.

There were several features of the MJ West African Monsoon simulation in CCSM4 that were viewed as deficient (Cook et al., 2012), and a number of these errors carried forward to CESM1. In general, as shown for CESM1 in Figure 11b compared to observations in Figure 11c and the differences in Figure 11f, there was too much rainfall over the Atlantic just south of the Guinean coast during MJ with differences exceeding +6 mm day$^{-1}$. Additionally, there was too much rainfall to the east over the Ethiopian region, with positive differences approaching +3 mm day$^{-1}$. During the latter part of the monsoon season in JAS in CESM1 (Figure 12), there was generally deficient rainfall over the equatorial African regions with negative differences of around −3 mm day$^{-1}$. All of these features are generally improved in CESM2. The MJ rainfall occurs more preferentially over the African coast in CESM2 (Figure 11a) compared to CESM1 (Figure 11b) with increases of about +3 mm day$^{-1}$ (Figure 11d). Though CESM2 still simulates excessive precipitation to the south of the Guinean coast, the simulation errors are about half of what they were in CESM1 (Figures 11e and 11f).

The 850 hPa wind simulation is improved in CESM2 compared to CESM1 with the southeast trades shifting to near the equator where they were near 5°S in CESM1 (cf. Figures 11a and 11b). However, the CESM2 trades are still about 3° of latitude south of where they are located in the observations at this time of year (Figure 11c). Additionally, rainfall over the Ethiopian region to the east is closer to observations (Figure 11c) in CESM2 (Figure 11a) compared to CESM1 (Figure 11b). These differences amount to about −3 mm day$^{-1}$ in that region (Figure 11d) with CESM2 having anomalies less than about +1 mm day$^{-1}$ compared to observations (Figure 11e). These improvements are seen in Table 1 as a higher pattern correlation with observations in CESM2 (0.82) compared to CESM1 (0.74) with a corresponding reduction of RMSE in CESM2 of 1.25 compared to 1.96 in CESM1.

The subseasonal monthly mean time evolution of zonal mean precipitation over the West African monsoon region also shows the early season precipitation maximum near 3°S during April–May in CESM1 (Figure 11j). This is not present in observations (Figures 11g and 11h) and is also not simulated in CESM2, which signifies a marked improvement in CESM2 (Figure 11i). The August precipitation maximum near 8°N is seen in both observational data sets and simulated with correct timing and latitude in CESM2 but with larger amplitude by about 20%. This is an improvement over CESM1 where that maximum was about 10% weaker than observations and shifted north about 4° of latitude.

Though changes in the convection scheme in CESM2 are responsible for some of these improvements, it is likely that the warmer base state SSTs in the tropical Atlantic in CESM2 (Figure 8e), compared to the cooler than observed SSTs there in CESM1 by nearly 2°C (Figure 8f), also contributed to a somewhat northward shift of the ITCZ to place it more over the Guinean coast with consequent reductions of precipitation deficits seen in CESM1 over West African land areas noted above.

With regards to the later part of the monsoon season (JAS, Figure 12), as noted above, the main error in CESM1 was that precipitation totals over equatorial Africa were too small (Figures 12b and 12f). This error has been lessened in CESM2 with differences in precipitation there amounting to values greater than +3 mm day$^{-1}$ or a nearly 50% increase in CESM2 compared to CESM1 (Figure 12d). The spatial pattern in CESM2 captures the maxima near the Guinean coast and Nigeria seen in observations (Figure 12c). If anything, JAS seasonal precipitation totals are now about 15% too large in CESM2 compared to observations (Figure 12e and lower panels of Figure 11). There is excessive precipitation in CESM2 over the Guinean coast with positive anomalies reaching nearly +2 mm day$^{-1}$ with some small deficits in the Sahel (Figure 12e). This precipitation feature is accompanied by 850 hPa westerlies near 10°N coming into West Africa from the Atlantic that are about 50% too strong in CESM2 (Figure 12a) as they were in CESM1 (Figure 12b) compared to observations (Figure 12c). As with the early season during MJ, the later season monsoon simulation is improved as documented in Table 1 with a higher pattern correlation (0.88 vs. 0.85 in CESM1) and reduced RMSE (1.03 vs. 1.33 in CESM1). As noted above, warmer base state SSTs in the tropical Atlantic in CESM2 compared to CESM1 likely contribute to the improvements in CESM2 of precipitation over land areas.
9. South African Monsoon

Previous studies have identified monsoon season rainfall over South Africa as potentially important to understanding global monsoon simulations (Nie et al., 2010; Zhang & Wang, 2008). Here we briefly describe some of the features of this southern summer (DJF) monsoon regime in CESM1 and CESM2.

Figure 11. Same as Figure 1 except for the May–June season in the west African monsoon; bottom four panels averaged from 10°W to 30°E.
While the error of excessive precipitation over South African land areas is shared by CESM1 and CESM2 (Figures 13e and 13f), the errors in CESM2 are reduced by about 20% over Namibia and Botswana in association with enhanced onshore flow from the southeastern Atlantic that carries more moisture farther east. Meanwhile, precipitation errors are increased by about that amount over eastern South Africa in CESM2 compared to CESM1 in part due to overly strong onshore flow from the southwestern Indian Ocean. Over the western Indian Ocean itself, the precipitation errors in CESM2 are larger than CESM1, with a large amplitude north-south dipole of errors of nearly 6 mm day$^{-1}$ near the equator and opposite-sign errors of nearly that magnitude near 15°S (Figure 13e). This pattern is not seen in CESM1 (Figure 13f).

The monthly evolution of the rainfall maximum over South Africa for observations shows a January maximum near 10°–15°S of about 6 mm day$^{-1}$ (Figures 13g and 13h). Both model versions simulate roughly this amplitude for the rainfall maximum, though CESM1 has the maximum shifted somewhat south to 15°S with the correct seasonal timing in January (Figure 13j). CESM2 has the simulated latitudes of the maximum closer to the observed values from 10°–15°S, but with the monthly peak shifted a month later to February. For this monsoon regime, the CESM2 for this entire area has a slight increase in pattern correlation of 0.86 to 0.87, but an increase in RMSE of 1.83 compared to 1.45 in CESM1. Thus, there is not an overall improvement for the South African rainy season in CESM2 compared to CESM1.

10. South American Monsoon

One of the systematic errors in the South American monsoon seasonal precipitation pattern (December–March, DJFM) in CESM1 was deficient precipitation in the central Amazon (Figure 14b cf. Figures 14a). That is, the precipitation maximum in CESM1 was centered too far east over eastern Brazil (Figure 14b) compared to observations where the precipitation maximum is more over central and western Brazil (Figure 14c). This produced precipitation deficits in CESM1 compared to observations of nearly −5 mm day$^{-1}$ in that region. These errors were accompanied by 850 hPa easterlies that were too strong and extended too far west between the equator and 10°S. The DJFM seasonal precipitation and surface wind simulation in CESM2 are improved in comparison to CESM1. There is more extensive precipitation over central and western Brazil (cf. Figures 14a and 14b) with positive differences of 3–6 mm day$^{-1}$ there (Figure 14d). The surface easterlies start to recurve to the southwest farther to the east in CESM2 (Figure 14a) compared to CESM1 (Figure 14b), which also is in better agreement with observations (Figure 14c).
It has been shown that the precipitation deficits over the Amazon in CESM1 likely had major contributions from deficiencies in the sensitivity of modeled deep convection to lower tropospheric moisture (Sakaguchi et al., 2018). Thus, an increased sensitivity to stable layers in the deep convection formulation (Zhang & McFarlane, 1995, and Neale et al., 2008), based on a reduction in the number of allowable negative

Figure 13. Same as Figure 1 except for southern Africa (DJF); bottom four panels averaged from 10–40°E.
Figure 14. Same as Figure 1 except for the south American monsoon (DJFM); bottom four panels averaged from 60–40°W.
buoyancy layers, enhances the moisture sensitivity of deep convection and likely contributes to a reduction of the dry bias over the Amazon in CESM2 compared to CESM1.

There is still excessive precipitation in CESM2 over eastern Brazil compared to observations that was also seen in CESM1, with anomalies of about +3 mm day$^{-1}$ (Figure 14a cf. Figure 14c, and differences from

Figure 15. Same as Figure 1 except for the north American monsoon (JJA); bottom four panels averaged from 115–100°W.
observations in Figure 14e). There is some reduction in this bias in CESM2 compared to CESM1 along the Atlantic coast in the Nordeste region of Brazil (Figure 14d). This likely has contributions from the changes in SST patterns simulated in CESM2 where there are now positive SST biases north of the equator (Figure 8e) compared to negative SST biases there in CESM1 (Figure 8f). This change in SST simulation in CESM1 would act to draw precipitation a bit north toward the warmer SSTs, thus contributing to the reduction of the precipitation error in that region. However, the excessive precipitation amounts simulated over most of the Nordeste region seen in CESM1 remain a significant shortcoming in CESM2.

Another systematic error in CESM1 was excessive precipitation extending too far to the south over the Andes in Bolivia and northern parts of Argentina and Chile (Figure 14b) with differences from observations of about +5 mm day$^{-1}$ (Figure 14b). Though this error has not totally gone away, CESM2 shows improvements in this aspect, with reductions of precipitation in those regions compared to CESM1 of about −3 to −6 mm day$^{-1}$ (Figure 14d). This is accompanied by a reduction in magnitude of 850 hPa winds in CESM2 compared to CESM1 near the Andes with reduced implied surface convergence that would contribute to less precipitation there in CESM2.

To track the evolution of the greater-than-observed precipitation over the northeast of Brazil (40 to 60°W), the time-latitude evolution of the wet season rainfall (Figures 14g–14j) reflects aspects of the season-mean rainfall. The precipitation maxima in the models occurs about a month too early compared to observations (in December as opposed to January) and becomes established too far south. This highlights the anomalous southward shift of the ITCZ in the models noted above that contributes to the excess simulated precipitation over this region.

The reduction in the precipitation errors in CESM2 noted above produce an increase in pattern correlation with observations for the South American monsoon from 0.86 in CESM1 to 0.88 in CESM2 and a corresponding reduction in RMSE in CESM2 to a value of 2.09 from 2.24 in CESM1 (Table 1).

### 11. North American Monsoon

A striking systematic error of seasonal (June–August, JJA) precipitation in the North American monsoon in CESM1 compared to observations (Figure 15b cf. Figure 15c) was excessive precipitation over coastal southern Mexico extending up into the U.S. Great Plains, with significant differences from observations for the latter of about +3 mm day$^{-1}$ (Figure 15f). There has been a marked improvement in CESM2 compared to CESM1, with reduction of those precipitation errors of about −4 mm day$^{-1}$ (Figure 15d) to bring CESM2 in much better agreement with the observations (cf. Figures 15a to 15c) where differences from observations in CESM2 in the Great Plains are near zero (Figure 15e). This is accompanied by an improvement in the simulation of 850 hPa wind direction in CESM2 compared to CESM1, with CESM2 showing more of a southeast component to 850 hPa wind coming in off the Gulf of Mexico (Figure 15a) in closer agreement with observations (Figure 15c), while CESM1 has more of a southerly component (Figure 15b). Additionally, the large anomalous precipitation maximum near 40°N, 105°W in CESM1 (Figure 15b) that is associated with easterly 850 hPa winds is much reduced in CESM2 (Figure 15a) along with a reduction of those anomalous easterlies in that region.

One error that remains in CESM2 is that the coastal northwestern Mexico precipitation maximum is still somewhat weaker than observed and does not extend far enough northward. The CESM2 has negative precipitation anomalies, compared to observations, of up to about −3 mm day$^{-1}$ along the northwestern Mexico coast comparable to what was simulated in CESM1 (Figure 15f).

The marked improvements in the subseasonal latitudinal evolution of the North American monsoon in CESM2 compared to CESM1 are shown in the lower panels of Figure 15. CESM1 had an anomalously large early onset of precipitation between 30° and 35°N in April with values of about 2.5 mm day$^{-1}$ (Figure 15j) while in both observational data sets (Figures 15g and 15h) and in CESM2 (Figure 15i), the maximum precipitation at those latitudes occurs in August–September with lower values of about 1–2 mm day$^{-1}$. Though not directly connected to the North American monsoon system, the midlatitude precipitation maximum near 45°N in June is much better simulated in CESM2 compared to CESM1, with the former having values closer to observed but with about 20% less amplitude, while CESM1 showed precipitation values over 4 mm day$^{-1}$, about twice the amplitude as the observations.
Major features of the northern realm of the North American monsoon are mesoscale convective systems (MCSs), and perhaps an improved simulation of those features could have contributed to the reductions in precipitation errors noted in Figure 15. Unfortunately, the simulation of MCS events has not improved in CESM2. Thus, the reduction of error in CESM2 (pattern correlation improves in CESM2 to 0.87 from 0.83 in CESM1, and RMSE of 1.01 in CESM1 is reduced to 0.96 in CESM2) likely has contributions from the improvements in the convection scheme as has been the case for a number of the monsoon regimes addressed above.

12. Conclusions

There have been a number of improvements to the various monsoon regimes around the world from CESM1 to CESM2. There is evidence of movement of the western Indian Ocean precipitation maximum to the east in CESM2 in somewhat closer agreement with observations. The precipitation maxima in the eastern Bay of Bengal and the coasts of Myanmar and Thailand, and land areas of Vietnam, Cambodia, and Laos, have increased in CESM2 in closer agreement with observations. Monsoon precipitation in CESM1 that extended too far to the northwest over Pakistan now is more contained to the southeast in CESM2. The seasonal timing of the south Asian monsoon, monsoon-ENSO connections, and monsoon intraseasonal variability all are improved in CESM2 compared to CESM1 and compare more favorably with observations. For the Australian monsoon, deficient precipitation over the Maritime Continent in CESM1 has been improved in CESM2 with increases of precipitation over the large tropical islands of Borneo, Celebes, and Papua New Guinea and decreases over southwestern Australia, all in closer agreement with observations.

In the West African monsoon, the MJ rainfall error in CESM1 of excessive rainfall over the Gulf of Guinea has been cut in half in CESM2, though rainfall there is still greater than observed. Rainfall over the Ethiopian region to the east is reduced in CESM2 compared to CESM1 in closer agreement with observations. In JAS in the West African monsoon, the main error in CESM1 of deficient precipitation totals over equatorial Africa has been lessened in CESM2, though CESM2 now simulates excessive precipitation over the Guinean coast with some small deficits in the Sahel. Though systematic errors over some areas of southern Africa are improved, there has been little net improvement in the overall simulation of monsoon precipitation over South Africa in CESM2 compared to CESM1.

The South American monsoon DJFM seasonal precipitation simulation in CESM2 is improved in comparison to CESM1 with regards to more extensive precipitation over the Amazon in central and western Brazil, and a reduction of the positive precipitation bias over the Atlantic coastal regions of the Nordeste, though there is still excessive precipitation over the northern part of the Nordeste region of Brazil compared to observations. An error in CESM1 was excessive precipitation extending too far to the south over the Andes in Bolivia and northern parts of Argentina and Chile, but CESM2 shows improvements with reductions of precipitation in those regions in closer agreement with observations.

A systematic error in the CESM1 North American monsoon simulation of excessive precipitation over coastal southern Mexico during JJA extending up into the U.S. Great Plains has been improved in CESM2, with reduction of those precipitation errors that brings CESM2 into better agreement with the observations, particularly over the Great Plains. Though somewhat improved from CESM1, in CESM2 coastal northwestern Mexico precipitation maximum is still weaker than observed and does not extend far enough northward.

The reasons for some of the improvements of monsoon features in CESM2 compared to CESM1 can be attributed to warmer base state tropical SSTs, as well as improved zonal gradients, and changes in the convection scheme. These factors in combination have had a particularly positive influence in CESM2 in not only improving the simulations of intraseasonal variability but also bringing land-based precipitation into better agreement with observations over many of the monsoon regions. These changes to the convective scheme are discussed in more detail in Danabasoglu et al. (2020), and several aspects can be identified as contributing to improving monsoon simulations in CESM2. First, an increased sensitivity to stable layers in the deep convection formulation (Zhang & Mcfarlane, 1995, and Neale et al., 2008), based on a reduction in the number of allowable negative buoyancy layers, enhances the moisture sensitivity of deep convection and enhances the moist mode nature of deep convection. Additionally, the increase of precipitation over land in CESM2, in closer agreement with observations in most monsoon regimes, is likely related to a
response to the MG2 rain production (prognostic) versus MG1 (diagnostic). In terms of the magnitude, it seems the increased humidity sensitivity in the deep convection is partly responsible, in addition to CLUUB in CESM2 versus UW in CESM1. These factors, combined with warmer SSTs within the equatorial belt compared to CESM1, means that convection is more readily able to initialize and contributes to larger values of precipitation over land areas involved with monsoon circulations. Additionally, intraseasonal variability is enhanced in that these changes to the convective scheme enable MJO and BSISO events to more readily initialize in the Indian Ocean and propagate eastward and northward, respectively.

Because the representations of monsoon regimes are not explicitly tuned or adjusted during the model development process, the monsoon simulations are the end product of many other changes and improvements that are made to multiple parameterizations and formulations in the model. However, what became clear late in the CESM2 development process was that warmer tropical SSTs and improvements to the convection scheme were having a clear impact on improving tropical precipitation in general and monsoon precipitation in particular. But as seen in Figure 8, there are still considerable systematic errors in tropical SSTs that can be improved, and presumably, this would contribute to better monsoon simulations in future model versions. And in any model, the convection scheme has effects on many aspects of a model simulation, not least of which are the monsoon simulations. Clearly, the improvements made to the convection scheme summarized above had major contributions to reducing monsoon errors in CESM2 compared to CESM1. Subsequent improvements to the convection scheme could be expected to contribute to consequent improvements in monsoon simulations in future model versions.

Model and Data Availability

Previous and current CESM versions are freely available online (at www.cesm.ucar.edu/models/cesm2/). The CESM solutions/data sets used in this study are also freely available from the Earth System; Grid Federation (ESGF) at esgf-node.llnl.gov/search/cmip6 or from the NCAR Digital Asset; and Services Hub (DASH) at data.ucar.edu or from the links provided from the CESM website (at www.cesm.ucar.edu). HADiSST data are available online (from https://www.metoffice.gov.uk/hadobs/hadisst/). GPCP precipitation data are available from the ESRL website (https://www.esrl.noaa.gov/pas/data/gridded/data.gpcp.html). The All-India Rainfall is available from the data.gov website (https://data.gov.in/catalog/all-india-area-weighted-monthly-seasonal-and-annual-rainfall-mm?filters%5Bfield_catalog_reference%5D=85825%26format=json%26offset=0%26limit=6%26sort%5Bcreated%5D=desc). The TRMM rainfall data are available from the NASA website (https://pmm.nasa.gov/data-access/downloads/trmm) and GPCP rainfall data from the ESRL website (https://www.esrl.noaa.gov/pas/data/gridded/data.gpcp.html). The ERA-I data are available from the ECMWF website (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). The Large and Yeager (2009) surface wind stress data are available online (from https://climatedataguide.ucar.educlimate-data/core2-air-sea-surface-fluxes).

Merra2 data are described in doi: 10.5065/D62R3QFS and available online (from https://doi.org/10.5065/D62R3QFS), Berkeley Earth Surface Temperature Project data available from the Berkeley Earth website (http://berkeleyearth.org/data/).

References


