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U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2020 Fourth Quarter Performance Metric: Evaluate Improvement in Simulations of Mesoscale Convective Systems from Parameterization Developments in E3SM

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1.0 Product Definition

Mesoscale convective systems (MCSs) consist of assemblies of cumulonimbus clouds on scales of 100 km or more and produce mesoscale circulations (Houze 2004, 2018). As the largest form of deep convective storms, MCSs contribute to 30%–70% of annual and warm season rainfall as well as over half of the extreme daily rainfall events in the U.S. east of the Rocky Mountains (Stevenson and Schumacher 2014, Feng et al. 2019, Haberlie and Ashley 2019). Since MCSs contribute importantly to mean and extreme precipitation in the U.S. and many other regions around the world, understanding how well they are simulated by E3SM may guide future development towards more skillful modeling of convective storms and associated hydrologic impacts.

The FY2020 Second Quarter Performance Metric Report documented comparisons of MCSs in the central and eastern U.S. in a high-resolution simulation produced by E3SM v1 at 25-km resolution (Caldwell et al. 2019) with observations. MCSs in the simulation occur less frequently and produce less intense precipitation, resulting in large underestimation of MCS volumetric rain-rate compared to observations. The FY2020 First and Third Quarter Performance Metric Reports indicated that these model biases in simulating MCSs can be attributed to model limitations in parameterizing convection, clouds, and other related processes, as well as model biases in simulating the MCS large-scale environment. Recently several new developments in parameterizing deep convection have been implemented in E3SM targeted for use in future E3SM versions. In this FY2020 Fourth Quarter Performance Metric Report, we evaluate MCSs simulated by E3SM with and without the new developments in convection parameterizations. The goal is to highlight aspects of MCSs that have been improved with the new model features and identify aspects that need more work to produce more realistic simulations of MCSs in the future. Overall, the new developments show a clear improvement in capturing the diurnal timing of MCS initiation and mature stages in the central U.S. as well as the frequency and intensity of MCSs over ocean in the Indo-Pacific sector. The frequency and intensity of MCSs are still substantially underestimated: effort is underway to address this bias by the incorporation of a stochastic convection scheme, an advanced cloud microphysical scheme, and higher-resolution representations of the MCSs.

2.0 Product Documentation

Impacts of two recent developments in convection parameterizations for E3SM v2/v3 on simulating MCSs are examined using E3SM simulations at ~25-km grid spacing. The tested new features are (1) a new convective triggering function that combines the dynamic Convective Available Potential Energy (dCAPE) trigger and the Unrestricted air parcel Launch Level (ULL) approach, i.e., the dCAPE-ULL trigger, described in Xie et al. (2019); and (2) the Multiscale Coherent Structures Parameterization (MCSP) described in Moncreff (2019).

The dCAPE-ULL trigger introduces a dynamic constraint on the initiation of convection that emulates the collective dynamical effects to prevent convection from being triggered too frequently, as well as to allow air parcels to launch above the boundary layer (BL) to capture nocturnal elevated convection. The former is to address the well-known problem with the deep convection scheme developed by Zhang and McFarlane (1995) (ZM hereafter) commonly used in earth system models including E3SM, which triggers convection too frequently, leading to spurious precipitation during daytime, particularly over land. The latter is to improve the model capability to capture nocturnal elevated convection that is often associated with propagating MCSs frequently found east of the Rocky Mountains in the U.S. and in other regions but missing in most climate models. Using the dCAPE-ULL trigger in E3SM has resulted in significant improvements in simulating the phase of the diurnal cycle of precipitation in the central U.S. by suppressing spurious convection during daytime and better capturing nocturnal elevated precipitation (Xie et al. 2019). However, no clear improvement is found in the amplitude of model precipitation, which is too weak compared to observations.

The MCSP scheme is developed specifically for representing MCSs in climate models in which they are currently missing as they are neither parameterized nor resolved (Moncreff 2019). The basic idea is to add a heating term that is representative of mesoscale heating observed in organized convection, which consists of heating in a stratiform region (in the upper troposphere), and equal magnitude evaporative cooling below (lower troposphere), as well as to consider mesoscale momentum transport. This additional vertical heating structure is proportional to the heating in the ZM scheme. Combining the MCSP scheme with the ZM scheme, initial analysis shows a reduction of heating produced by the ZM scheme, indicating the impact of the MCSP scheme in suppressing deep convection in the model. Overall, the impact of MCSP in E3SM is primarily on tropical waves (e.g., Kelvin wave) and Madden-Julian Oscillation (MJO), which are much improved. Its impact on mean precipitation is minor, generally with slightly weaker precipitation seen over land and slightly stronger precipitation over ocean.

The results discussed in this metric report are based on 3-year-long atmosphere-land simulations with present-day forcing for the year 2010 along with weekly sea surface temperature (SST) and sea ice prescribed from the observations for years 2010−2012. In addition to examining the individual impacts of the two new features (dCAPE-ULL and MCSP) on MCSs, their combination is also tested to understand their overall effect. Table 1 summarizes the simulations performed for this report. Notably, previous efforts only tested dCAPE-ULL and MCSP in low-resolution simulations (~100 km). Although the impacts of dCAPE-ULL and MCSP on precipitation have been evaluated in previous studies, their influence on MCS has not been specifically investigated. Furthermore, these new model features have not been tuned for simulations at 25-km grid spacing, which is important for optimizing model performance (e.g., Caldwell et al. 2019). Hence the results presented in this report represent an initial effort to evaluate the impacts of the new features on MCS simulation at 25-km grid spacing, which will be followed by more extensive testing and evaluation as guided by the preliminary results reported here.

Similar to the second quarter metric report, MCSs in observations and model simulations are tracked using an updated version of the MCS tracking algorithm (Feng et al. 2020), which is adjusted for use with datasets at 25-km grid spacing. Given that both dCAPE-ULL and MCSP have shown a larger impact on mean precipitation in the tropics, the Indo-Pacific sector where MCSs occur frequently is also selected in the analysis besides the central U.S. In this report, an MCS is defined as a large cold cloud system (CCS) with brightness temperature (Tb) < 241 K and an area exceeding 6 x 104 km^2 that contains a precipitation feature (PF) with major axis length > 100 km. Furthermore, the PF area, mean rain rate, and rain rate skewness must be larger than the lifetime-dependent thresholds. An MCS is identified when both conditions of CCS and PF are met continuously for longer than 6 hours. For the E3SM simulation, hourly precipitation and outgoing longwave radiation are used to track MCSs. In addition, MCS criteria for E3SM have been relaxed compared to observations to allow more tracked MCSs for diagnostic purposes. The CCS area and duration are reduced by 50% to 3 x 104 km^2 and 3 hours, and the PF area, mean rain rate and rain rate skewness are also relaxed. For observations in the central U.S., hourly satellite infrared data and Next-Generation Radar Network (NEXRAD) precipitation data for the same years as the model, coarsened to 25-km resolution, are used to track MCSs for comparison.

In the Indo-Pacific sector, the 10-km hourly GPM satellite IMERG V06B precipitation data is used. The GPM IMERG precipitation data is a unified precipitation retrieval data set from a network of partner satellites in the GPM constellation (Huffman et al. 2019). The primary precipitation estimates in IMERG is from passive microwave (PMW) sensors. A quasi-Lagrangian interpolation scheme is applied to the gridded PMW precipitation estimates to fill in the gaps between PMW overpasses using motion vectors derived from total precipitable water vapor from numerical models in V06 (Tan et al. 2019). The IMERG V06B data used in this report has 0.1° x 0.1° and hourly resolution. MCS tracking in the Indo-Pacific region uses slightly different PF criteria as that in the U.S. to adapt for use with the IMERG precipitation data set. The PF thresholds for the IMERG satellite data are chosen to best match NEXRAD-based MCS statistics over the U.S. Results reported here are for the boreal summer season (June-July-August, JJA) that represents an even bigger challenge for E3SM to capture MCSs than the spring season (see the second performance metrics report), but similar model behaviors are found in the spring season.

Table 1. Summary of model experiments.

Model ID	Description	Reference
CTL	Default low-resolution (0.25º, 72L) E3SM v1	Xie et al. (2018), Rasch et al. (2019)
dCAPE-ULL	Same as CTL, but with the dCAPE-ULL trigger	Xie et al. (2019)
MCSP	Same as CTL, but with the MCSP scheme	Moncrieff (2019)
dCAPE-ULL-MCSP	Same as CTL, but with both the dCAPE-ULL trigger and the MCSP scheme	Xie et al. (2019), Moncrieff (2019)

3.0 Results

3.1 MCSs Simulated in U.S.

Figure 1 compares the observed and E3SM-simulated precipitation during summer in the central and eastern U.S. The default model (CTL) largely underestimates the observed precipitation in the central U.S. (indicated by the box) while producing excessive precipitation in the southeastern U.S. Note that a majority of precipitation observed in the central U.S. is associated with eastward propagating MCSs that originate near the foothills of the Rocky Mountains in the late afternoon and produce precipitation in the central U.S. in the evening and mid-night. So, the model error in the central U.S. largely reflects its inability to capture the nocturnal precipitation systems associated with MCSs as demonstrated in the previous performance metric reports. The excessive precipitation seen in the southeastern region, where precipitation often peaks in late afternoon in observations, is primarily associated with the default ZM that triggers convection too frequently during daytime over land due to unrealistic coupling of convection with surface heating as discussed earlier. These model biases are clearly demonstrated in Figure 2, which compares the observed and simulated diurnal cycle of precipitation. CTL largely overestimates precipitation between 0900 and 1600 local solar time (LST) and underestimates precipitation in late afternoon and at night.

Overall, the new developments of convection parameterizations have provided little help in reducing the large dry biases in the central U.S., with only slight improvements evident in the Midwest with the use of dCAPE-ULL (Figures 1c and 1e), likely attributed to nocturnal precipitation better captured by the new trigger as shown in Figure 2. In contrast, MCSP produces even less precipitation than CTL in this region partly because convection is suppressed by the mesoscale heating that reduces the overall heating. In the southern and eastern regions, all the new features clearly reduce precipitation through various mechanisms that suppress convection, as discussed earlier. This helps to reduce the wet biases in CTL except for the coastal regions (including Florida) where the new changes further worsen the dry biases in CTL. In general, MCSP produces slightly better simulation near the coasts than dCAPE-ULL. With both dCAPE-ULL and MCSP, the biases over the central U.S. remain but some significant improvements are seen over the southern and eastern regions.

Consistent with Xie et al. (2019), the dCAPE-ULL trigger results in a significant improvement in capturing the phase of the diurnal cycle of mean precipitation amount in the central U.S in the high-resolution simulations (Figure 2). However, the amplitude is too weak compared to the observations. The diurnal cycle of precipitation in MCSP is similar to CTL, but with a much smaller amplitude across the day. dCAPE-ULL-MCSP generally reflects the combined features of these two modifications. Further model tuning and optimization are needed to fully utilize the improved features provided by these two new parameterization developments.

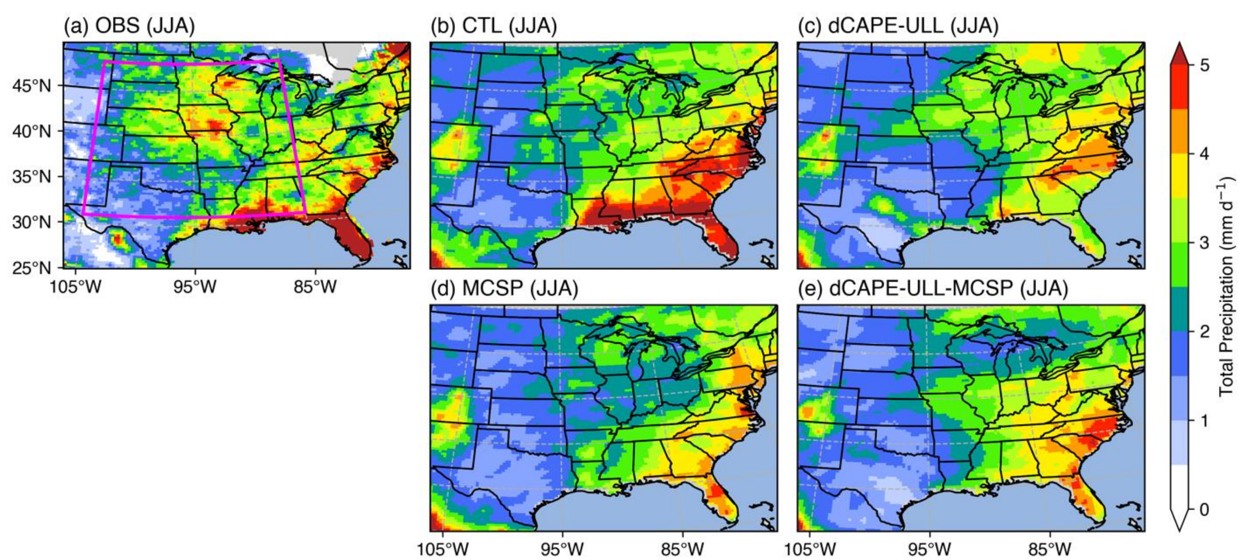

Figure 1. Observed and E3SM-simulated total precipitation during summer (JJA) in the central and eastern U.S.

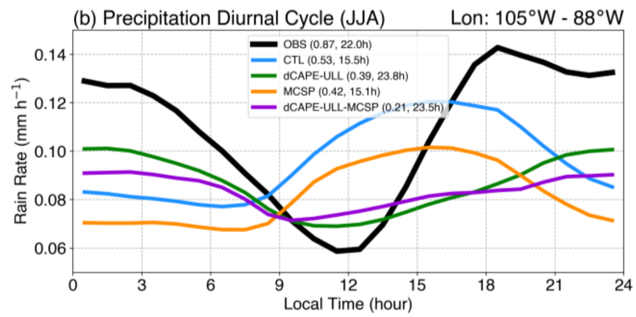

Figure 2. Observed and E3SM-simulated diurnal cycle of total precipitation during summer (JJA) for the central U.S. (denoted by the magenta box in Figure 1a).

Given the significant dry bias shown in Figure 1, it is not surprising to see that summer precipitation produced by MCSs in the central U.S. is substantially underestimated in all the models (Figure 3). While the default model produces 79% of the observed MCS numbers as a result of the relaxed PF criteria in the MCS tracking algorithm as described in Section 2.0, the new features further reduce the number of MCS relative to CTL (Table 2). The better-captured nocturnal mean precipitation amount in dCAPE-ULL does not lead to an improvement in simulation of MCSs due to noticeable reduction of the frequency of moderate to heavy rain rate (1-20 mm/hr). Further analysis indicates that nocturnal precipitation in dCAPE-ULL is almost entirely associated with much weaker non-MCS precipitation (not shown). However, the diurnal timing of MCSs is much better simulated by dCAPE-ULL compared to CTL as expected. As shown in Figure 4, most MCSs in dCAPE-ULL initiate in late afternoon (1800 LST) and reach their mature stage at midnight, similar to the observations. In contrast, CTL shows that the frequency of MCS initiation time and mature time have little to no diurnal cycle. MCSP shows the largest error in the diurnal timing of MCSs compared to other schemes. More analysis is needed to further diagnose the cause of the degradation in performance with MCSP in this region.

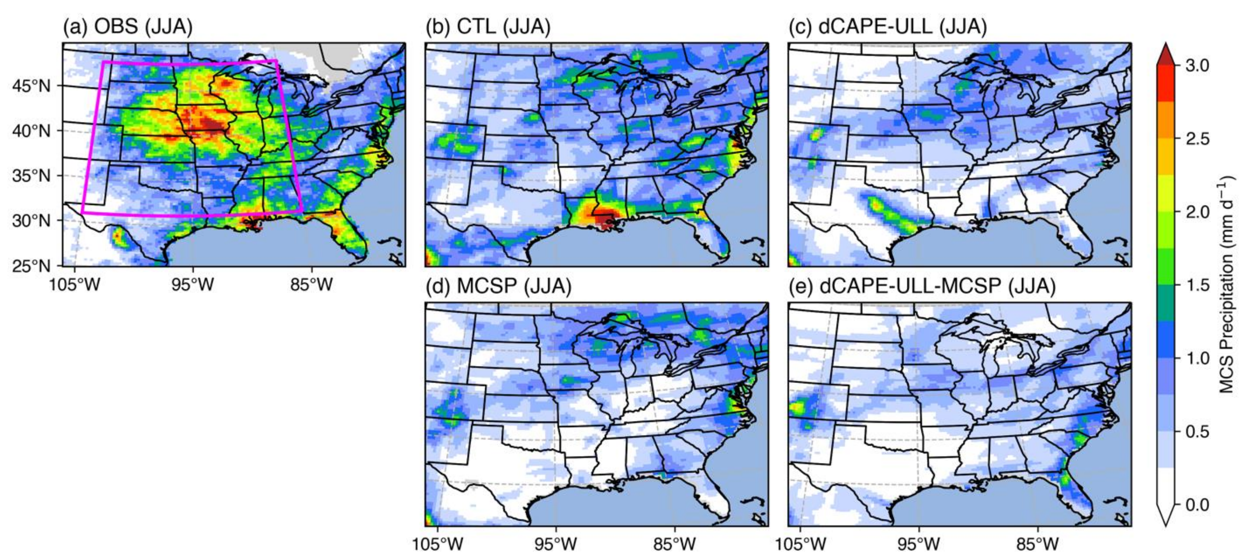

Figure 3. Same as Figure 1 except for MCS precipitation.

Table 2. The average number of MCSs during summer (JJA) in the central U.S. and the Indo-Pacific sector shown in the inset of Figure 6a. Percent values in parentheses are changes with respect to CTL.

	OBS	CTL	dCAPE-ULL	MCSP	dCAPE-ULL-MCSP
Central U.S.	85	67	38 (-44%)	46 (-32%)	34 (-49%)
Indo-Pacific Sector (ocean)	755	390	403 (3%)	439 (13%)	404 (4%)
Indo-Pacific Sector (land)	413	163	116 (-29%)	114 (-30%)	96 (-41%)

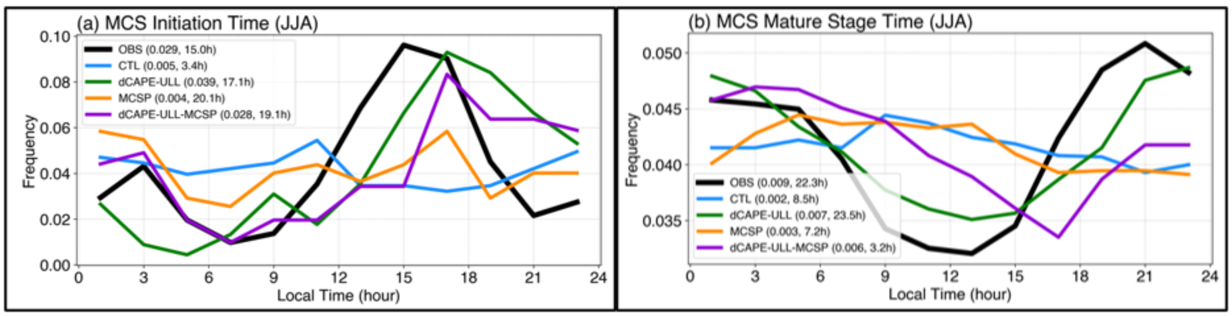

Figure 4. Summer MCS diurnal timing in the central U.S. (a) MCS convective initiation timing, and (b) MCS mature stage (PF major axis length > 100 km) timing. The diurnal cycle amplitude and phase for each data source are shown in the legend.

Although all the simulations significantly underestimate the frequency and intensity of MCSs, they capture well the observed MCS lifetime, but the MCS PF diameter is larger, and the PF mean rain rate is significantly weaker, resulting in too frequent low PF volume rain rate and insufficient high PF volume rain rate (Figure 5). From these analyses, we can infer that the model mainly fails in simulating MCS because of its inability to simulate the intense precipitation typically produced by MCS events, resulting in significant underestimation of MCS number. This challenge could be addressed by several ongoing model parameterization developments in E3SM that have shown some encouraging results in reducing the long-standing "too frequent, too light" precipitation bias in climate models. This will be further discussed in the summary of the report.

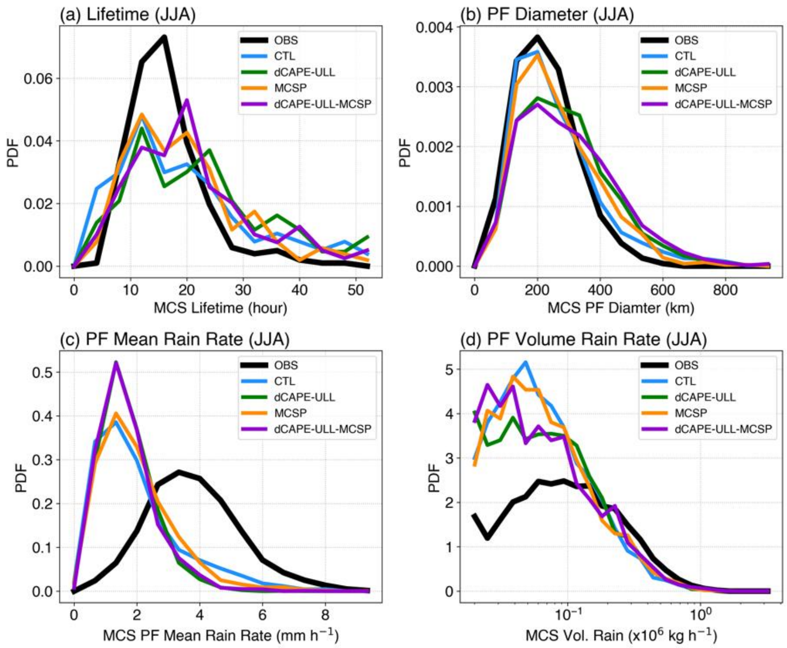

Figure 5. The observed and simulated properties of MCSs during summer in the central U.S.

3.1 MCSs Simulated in the Indo-Pacific Sector

In the Indo-Pacific region, all the new schemes show better skill in simulating precipitation than the default model. In particular, the dry biases in the Bay of Bengal and the western Pacific in CTL are considerably reduced with the new features (not shown). As indicated by the distribution of total precipitation rates over the region (Figure 6a), the increased precipitation amount produced by the new features is related to a shift from light precipitation to moderate and/or heavy precipitation. The new dCAPE-ULL trigger results in a considerable increase in precipitation with rain rate larger than 10 mm/hr. The increase of precipitation in MCSP is mainly for rain rate between 1 mm/hr and 10 mm/hr. These changes are even more clearly demonstrated in normalized accumulated rain amount (Figure 6b). The increase of moderate and heavy precipitation primarily occurs over ocean (not shown). Over land, the changes resulting from the new features are small, with MCSP even reducing the frequency of heavy precipitation (>10 mm/hr).

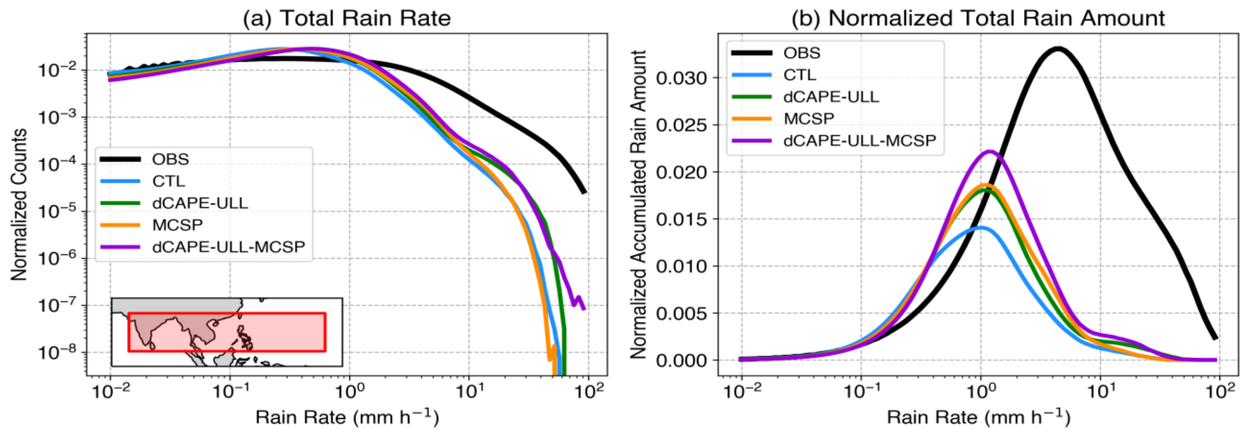

Figure 6. Observed and E3SM-simulated distribution of grid level total precipitation rates over the Indo-Pacific sector (see inset map). Note that the OBS (IMERG V06B) data has higher horizontal resolution (0.1°) than E3SM (0.25°) and hence more frequent intense rain rate is expected. In future comparisons, the IMERG data will be regridded to match the E3SM resolution, similar to regridding of the NEXRAD data to match the E3SM resolution in the central U.S.

Consistent with the changes in precipitation distribution, there is a slight increase of the average number of MCSs over ocean and a noticeable decrease over land with these new features (Table 2). The increase in the number of oceanic MCS is more noticeable over the South Asian monsoon region (not shown). As a result, MCS precipitation is also largely improved with the new features over the ocean areas where MCSP shows bigger improvement than dCAPE-ULL (Figure 7). It is interesting to see that combining these two changes yields the best result in simulating MCSs over this region. However, all simulations still substantially underestimate the frequency and intensity of MCSs although encouraging improvements are notable from the new developments.

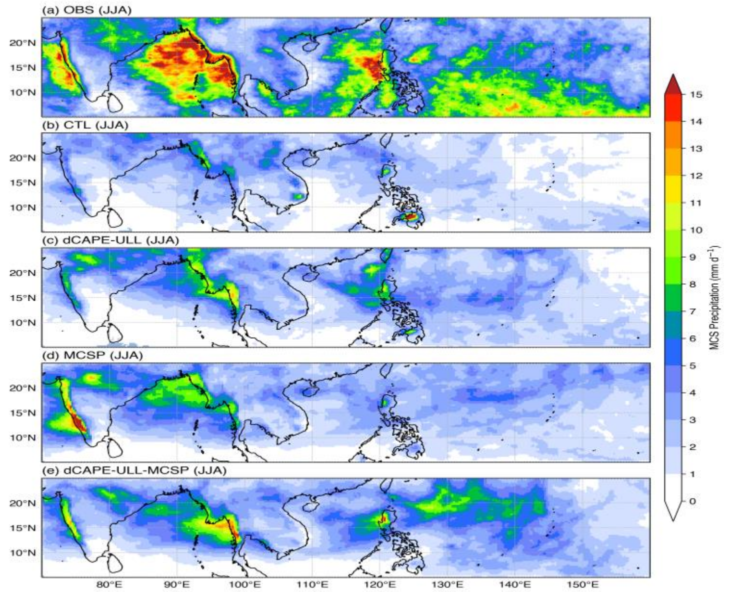

Figure 7. Same as Figure 3 except for the Indo-Pacific sector.

In summary, this performance report examined the impact of the newly developed convective trigger (dCAPE-ULL) and the multiscale coherence system parameterization (MCSP) on simulation of MCSs in both the central US and the Indo-Pacific sector. An MCS tracking analysis is applied to both observations and E3SM simulations at 25-km grid spacing to evaluate MCS precipitation characteristics simulated by the model with and without the new features. Results from this analysis illustrate the challenge for E3SM to capture MCSs; more specifically the frequency and intensity of MCSs are substantially underestimated in all the simulations and in both the selected midlatitude and tropical regions. Nevertheless, some encouraging features are evident from the new developments. In the central U.S., the use of the dCAPE-ULL trigger has led to a clear improvement in capturing the diurnal timing of MCS initiation and mature stages. This results from an improved simulation of nocturnal precipitation frequency. In the Indo-Pacific sector, both dCAPE-ULL and MCSP have led to a considerable increase in frequency and intensity of MCSs over ocean. This is due to a shift of precipitation frequency from light rain to moderate/heavy rain. In the tropical region, the new features have larger and positive impact on MCS simulation over ocean than land. Over land, dCAPE-ULL and MCSP help suppress spurious noon-time convection caused by the unrealistic coupling of convection to surface heating in the default model. However, this leads to even fewer and weaker MCSs simulated over land compared to the default model.

All the models reasonably capture the MCS lifetime, with larger precipitation feature (PF) diameter and weaker PF mean rain rate, resulting in too frequent low PF volume rain rate and insufficient high PF volume rain rate for MCSs that are produced. Therefore, the challenge for the model is to improve the simulation of intense precipitation characteristics of rainfall produced by the convective core of MCS. One way to address the challenge is to further increase model resolution to a grid spacing at which MCS structures can be mostly resolved. This is feasible in the near future through the ongoing development of a global storm-resolving modeling capability on exascale computers. At the same time, improving modeling of cloud and convective processes in earth system models at 25-km to 100-km grid spacing is important for improving long-term projections of water cycle, biogeochemical cycle, and cryosphere changes. In our first quarter report, we have demonstrated that replacing the Morrison-Gettelman cloud microphysics scheme (MG2, Gettelman and Morrison 2015) currently used in E3SM with the Predicted Particle Properties (P3) cloud microphysical scheme (Morrison and Milbrandt 2015) can lead to considerable improvements in simulating MCS frequency and intensity by increasing the frequency of heavy rain-rates. Another ongoing effort to incorporate a stochastic convection scheme in E3SM may also improve the representation of MCSs. Initial testing of the stochastic scheme has shown dramatic increases in heavy precipitation and reductions in light precipitation (Wang et al. 2020). These features will be integrated and optimized along with other developments for better simulation of MCSs and other climate features in E3SM.

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