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FY 2020 First Quarter Performance Metric: Develop and Test New Parameterizations for Representing Mesoscale Convective Systems in E3SM

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1.0 Product Definition

Mesoscale convective systems (MCS) are a complex of thunderstorms that develop into a single entity with precipitation covering hundreds of kilometers and persist for several hours or more (Houze 2004, 2018). They influence the climate system by (1) releasing latent heat that drives the general circulation, (2) providing a dominant source of precipitation in many regions, (3) redistributing and removing moisture, clouds, and aerosols, and (4) affecting the radiative transfer in the atmosphere. An important element for accurately representing the features of MCS in Earth system models is the simulation of cloud microphysical processes and their interaction with relevant dynamical processes. Significant shortcomings exist in the Gettelman and Morrison (2015) (MG2) cloud microphysics model currently used in the Energy Exascale Earth System Model (E3SM) model. These include: (1) MG2 does not consider rimed precipitating ice particles (graupel/hail), which are important contributors to precipitation in MCS, and (2) MG2 artificially partitions frozen particles into cloud ice and snow based on fixed parameters, which is unphysical (Morrison and Milbrandt 2015). These limitations are becoming untenable in simulating cloud and precipitation for addressing water cycle science questions as E3SM increasingly resolves strong updrafts that produce rimed particles.

The Predicted Particle Properties (P3) is a recently developed cloud microphysics model (Morrison and Milbrandt 2015, Morrison et al. 2015) that addresses the above limitations. It has more advanced treatments of ice microphysics parameterization in which ice particle properties such as the relative degree of riming and vapor deposition in their growth are predicted and evolve locally. P3 has been implemented into the E3SM model in order to improve the simulation of microphysical processes associated with mesoscale convective systems.

In this document, we test the performance of E3SM using the P3 microphysics compared to the original MG2 microphysics at a regionally refined mesh of ¼-degree grid spacing over the Contiguous United States. E3SM simulations are evaluated against observational data from the Next Generation Weather Radar (NEXRAD) network. The results show that the inclusion of rimed hydrometeors in the P3 microphysics improves the probability distribution function of simulated precipitation rates and MCS characteristics such as number, duration, and size. However, improvements are still needed to better simulate the diurnal cycle of MCSs and the partitioning of precipitation between MCS and non-MCS events. In future work, P3 will be extended to better represent additional microphysical processes such as hydrometeor sedimentation and evaporation. Additionally, non-hydrostatic dynamics are being implemented in E3SM, which will allow the model to be applied at higher resolution down to grid spacing of a few kilometers on which the role of cloud microphysics parametrization in MCS simulations can be better estimated.

2.0 Product Documentation

Since P3 was originally designed for high-resolution weather models at kilometer-scale grid spacings, changes are necessary to adapt the scheme to the coarser grid spacings and larger time steps used in E3SM. Changes include cloud/precipitation fraction treatment, subgrid distribution of hydrometeors, and homogenous aerosol freezing for cirrus clouds. We have also modified the coefficients for autoconversion and accretion process rates to be consistent with the adjustments recently made in MG2 for climatology simulations.

Evaluation of MCS in E3SM was carried out for simulations using a regionally refined mesh (RRM). The Great Plains of the U.S. provide an excellent venue for studying continental long-lasting and propagating MCSs. Therefore, an RRM of ¼-degree grid spacing was set up for the Continental United States (CONUS) using the E3SM Atmosphere Model Version 1 (EAMv1) as shown in Figure 1. In this configuration, CONUS has a grid spacing of 25 km and the rest of the globe has a grid spacing of 110 km. To reduce model uncertainties caused by modeled large-scale circulation, a linear nudging technique is employed to constrain the large-scale circulation from reanalysis data (Zhang et al. 2014, Sun et al. 2019). Two model simulations were run using the microphysics schemes of P3 and MG2, respectively, with a simulation time period from 1 January to 30 September 2011. Analysis is performed for the spring season (March-April-May 2011) during which there were several MCSs observed.

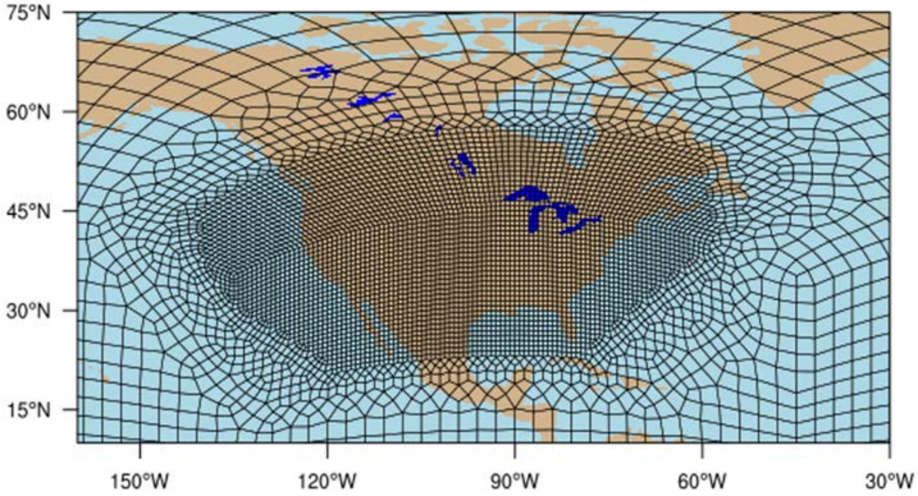


Figure 1. A regionally refined grid configuration for the atmosphere and land over the Continental United States in the Energy Exascale Earth System Model Atmosphere Model version 1. The high-resolution area has a grid spacing of 25 km, while the lower-resolution area has a grid spacing of 110 km.

We have developed an algorithm to track MCSs at 25-km grid spacing based on the method of Feng et al. (2019) for the 4-km grid of the radar data. The new tracking algorithm for the 25-km grid has been validated by comparing the tracked MCS properties with those from tracking of the 4-km data based on the NEXRAD. Then the same tracking algorithm is applied to the simulations to obtain the modeled MCS properties.

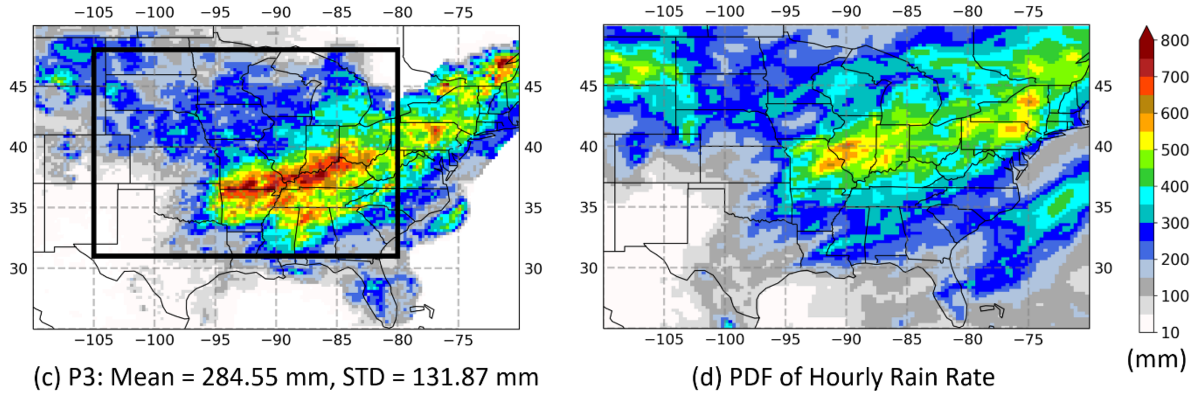
3.0 Results

We first looked into the spatial distribution of total precipitation for the entire spring season in 2011. Both the MG2 (Figure 2b) and P3 (Figures 2c) simulations generally capture the observed spatial pattern from the Stage IV precipitation data (Figure 2a). The stage IV precipitation data offer hourly estimates of NEXRAD radar-indicated, rain-gauge-corrected precipitation at a roughly 4-km spatial resolution. Here we regridded the data to compare with model simulations at the 25-km grid spacing. Although both simulations show a severe underestimation over the Midwest, P3 simulates higher values over the precipitation core regions (i.e., the states of Michigan and Illinois) and has less wet biases over the Rocky Mountains (e.g., the states of Montana and Wyoming) compared to the MG2, agreeing better with the observation. Note that all the further quantitative evaluations of precipitation, MCS features, and microphysical properties are performed for the domain confined by the black box in Figure 2a, which corresponds to the highest data quality of Stage IV precipitation data.

A more obvious improvement by the P3 scheme compared with total precipitation is the probability density function (PDF) of the hourly precipitation rates (Figure 2d). P3 simulates higher frequencies for rain rates larger than 20 mm hr^{-1}, whereas MG2 totally missed the heavy rain rates ≥ 32 mm hr^{-1}. The improvement with P3 in simulating large rain rates associated with MCSs is expected because of the added rimed precipitating particles.

(a) Ob: Mean = 270.46 mm, STD = 171.05 mm

(b) MG2: Mean = 284.97 mm, STD = 118.37 mm



(c) P3: Mean = 284.55 mm, STD = 131.87 mm

(d) PDF of Hourly Rain Rate

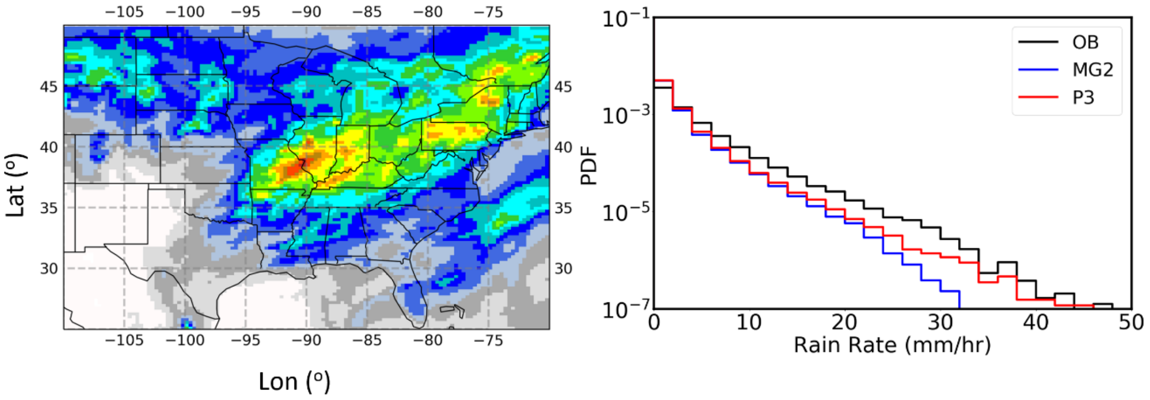


Figure 2. Comparison of March-May 2011 accumulated precipitation among (a) Stage IV precipitation, (b) MG2, and (c) P3. Panel (d) shows PDFs of hourly rain rates, where the Stage IV data are in black, MG2 in blue, and P3 in red.

We conducted MCS tracking and separately examined the diurnal cycle of MCS precipitation and non-MCS precipitation as shown in Figures 3-4. First, both P3 and MG2 underestimate the nocturnal total precipitation but overestimate the daytime precipitation. P3 simulates more nocturnal and less afternoon precipitation, which agrees better with observations. However, the magnitude of changes is not large enough to shift the phase of diurnal cycle. Secondly, the observed precipitation is primarily from MCSs but the model (using either P3 and MG3) does not produce the correct partitioning between MCS and non-MCS precipitation. The severe underestimation of MCS precipitation by the model might be a problem associated with under-representing or missing key mesoscale processes in cumulus parameterizations. P3 indeed improves the MCS precipitation by ~ 40% at nighttime, which is significant, due to the improvement of simulation of large rain rates.

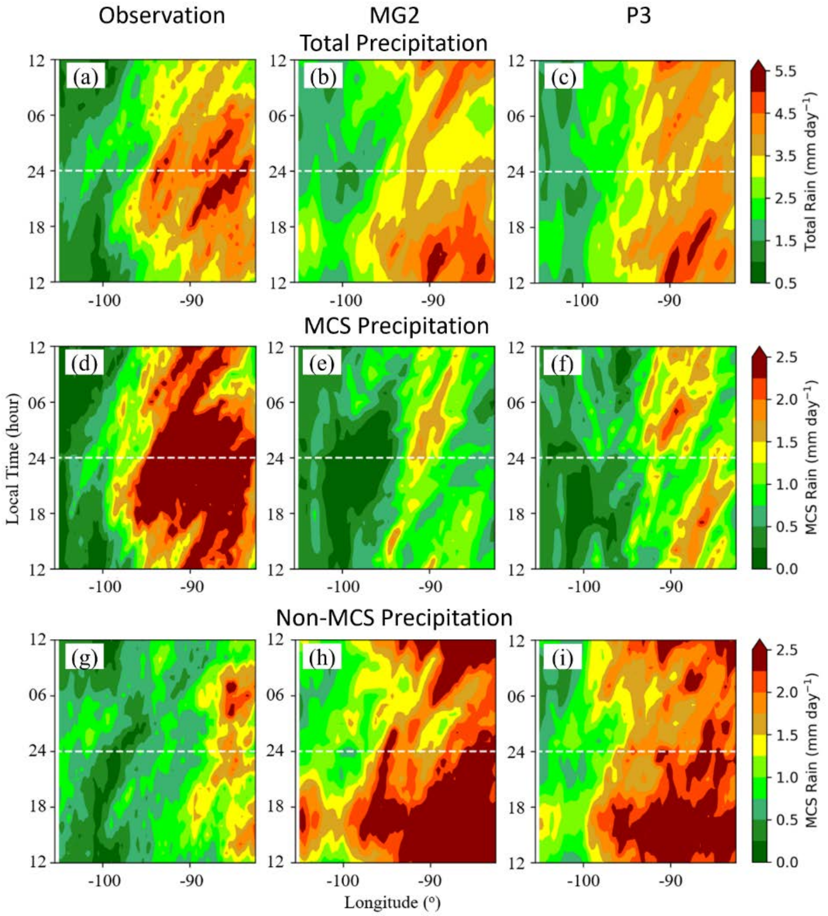
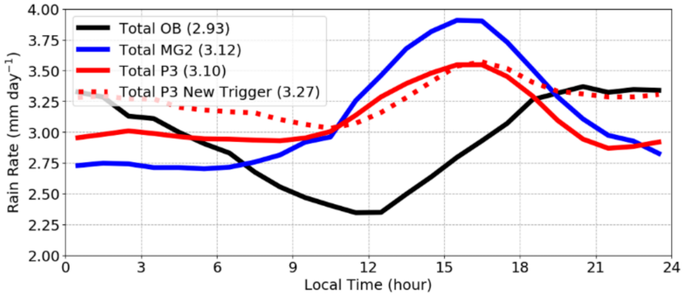


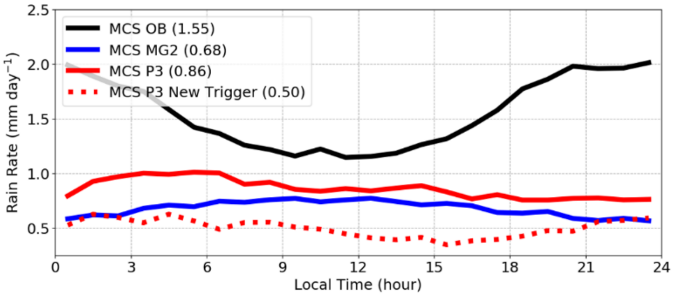
Figure 3. Hovmöller diagrams of total precipitation from (a) Stage-IV observation (left), (b) MG2 (middle), and (c) P3 (right) for March-May 2011. The second and third rows show the corresponding plots for MCS and non-MCS precipitation, respectively.

The ZM cumulus parameterization (Zhang and McFarlane 1995) used in E3SM was modified to improve the diurnal cycle of the precipitation at 1-degree grid spacing in a new study (Xie et al. 2019). We tested the new triggering employed in Xie et al. (2019) based on the simulation of P3. We find some improvement in nocturnal precipitation, but the magnitude is also not large enough to change the phase of the diurnal cycle (Figure 4). It is also noted that the MCS portion of precipitation is further reduced with the new triggering. This is because the rain rates become much weaker, so fewer precipitation events meet the criteria to be identified as MCSs. These results suggest potential scale-awareness issues with the new triggering and that additional model tuning might be needed to make the new trigger work well for the ¼-degree grid spacing in the regionally refined configuration.

(a) Total Precipitation



(b) MCS Precipitation



(c) Non-MCS Precipitation

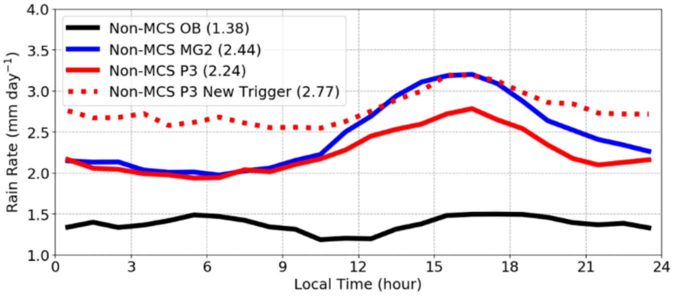


Figure 4. Diurnal cycle of (a) total precipitation, (b) MCS precipitation, and (c) non-MCS precipitation from Stage IV observation, MG2, P3, and P3 with the new convection triggering of Xie et al. (2019) for March-May 2011.

To further quantify the performance of P3 in MCS simulation in comparison with MG2, the spatial distribution of accumulated MCS precipitation amount and occurrence frequency during spring 2011 are shown in Figure 5. Although both simulations severely underestimate the MCS precipitation over the entire central U.S., comparing with MG2, P3 simulates 27% more precipitation, and the MCS precipitation core is better collocated with the observations. The improved simulation of MCS precipitation amount by P3 is because more precipitation events satisfy the criteria to be identified as associated with MCSs (Figure 5d-f). Based on the MCS numbers, 11 more MCSs are identified during the spring season of 2011 in the P3 simulation (Table 1). These 11 MCSs identified in P3 but missed in MG2 are responsible for about half of the differences of total MCS precipitation between P3 and MG2.

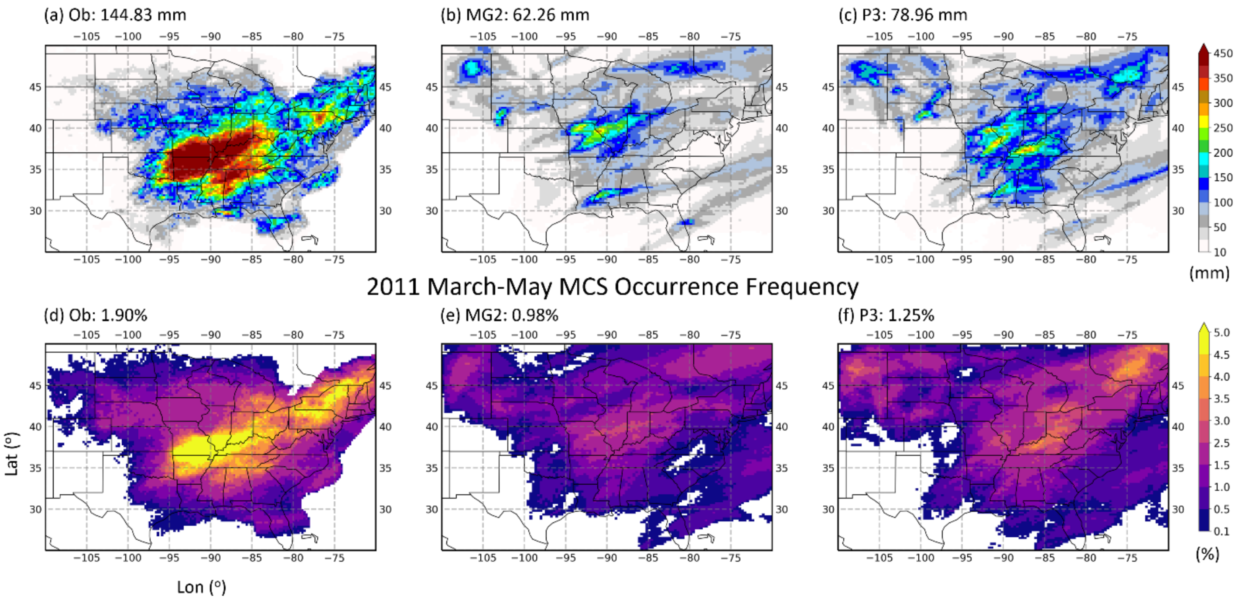


Figure 5. Comparison of accumulated MCS precipitation amount among (a) observation, (b) MG2, and (c) P3 and their respective occurrence frequency of MCS in (d), (e), and (f).

Table 1. The statistics of MCS tracking results.

	Observation	MG2	P3
Number of MCSs	111	53	64
Duration (hr)	18.9	18.6	23.8
MCS Diameter (km)	292.2	106.4	137.3

Given the fact that MCSs are defined based on a series of thresholds regarding the precipitating area, duration, precipitation intensity, etc., we examine what criteria prevents some of them from being identified as MCSs in MG2. We find that in the MG2 simulations, weak precipitation rates occur much more frequently and large rain rates occur more rarely compared with the P3 simulation, so more precipitation events fail to meet the precipitation intensity threshold for MCSs. Lacking the large rain rates in MG2 is associated with the absence of rimed process that produces graupel and hail that fall much faster than snow. Although precipitating more heavily in P3, MCS precipitation area is larger and the duration is longer (Table 1). This is likely associated with a strong microphysics feedback to the dynamics. We find that the large-scale ascending motion is 2-3 times stronger for large rain rates in P3 compared with MG2. In addition, more moisture is transported to higher altitudes from low altitudes as a result of the strong ascending motion, further helping to produce stronger and larger MCSs. The stronger large-scale ascending motion in P3 is likely initiated by the stronger ice microphysical processes (mainly deposition and riming), which release more latent heating feeding back to the dynamics.

In summary, we demonstrate that even at relatively coarse grid spacings (~25 km), without appropriately considering rimed hydrometeors for cloud microphysics, large precipitation rates associated with MCSs cannot be simulated, producing a PDF of precipitation rates that is skewed to the lower precipitation rates. The P3 microphysics implemented in the E3SM v1 model improve the PDF of precipitation rates and hence influence MCS characteristics such as number, duration, and size. P3 is being further developed into a 3-moment scheme, which better represents microphysics processes, particularly sedimentation and evaporation. Therefore, better performance can be expected in the future.

At the ¼-degree (~25 km) grid spacing, the role of cloud microphysics in precipitation is still limited because mesoscale and local-scale processes are represented by cumulus parameterization rather than explicitly resolved. This limits the improvements to the precipitation that can be achieved by microphysics parameterizations. As non-hydrostatic dynamics in E3SM has been implemented, allowing the model to be applied at higher resolution down to grid spacing of a few kilometers, much more significant impacts of the improved microphysics parameterization on precipitation are expected. The development of P3 laid the foundation for improving physics parameterizations for global storm-resolving simulations that will be used in addressing water cycle questions in future E3SM versions.

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