Can the Multiscale Modeling Framework (MMF) Simulate the MCS-Associated Precipitation Over the Central United States?

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Abstract Mesoscale convective systems (MCSs) are a major source of precipitation in many regions of the world. Traditional global climate models (GCMs) do not have adequate parameterizations to represent MCSs. In contrast, the Multiscale Modeling Framework (MMF), which explicitly resolves convection within the cloud-resolving model embedded in each GCM column, has been shown to be a promising tool for simulating MCSs, particularly over the Tropics. In this work, we use ground-based radar-observed precipitation, North American Regional Reanalysis data, and a high-resolution Weather Research and Forecasting simulation to evaluate in detail the MCS-associated precipitation over the central United States predicted by a prototype MMF simulation that has a 2° host-GCM grid. We show that the prototype MMF with nudged winds fails to capture the convective initiation in three out of four major MCS events during May 201x1 and underpredicts the precipitation rates for the remaining event, because the model cannot resolve the mesoscale drylines/fronts that are important drivers for initiating convection over the Southern Great Plains region. By reducing the host-GCM grid spacing to 0.25° in the MMF and nudging the winds, the simulation is able to better capture the mesoscale dynamics, which drastically improves the model performance. We also show that the MMF model performs better than the traditional GCM in capturing the precipitation intensity. Our results suggest that increasing resolution plays a dominant role in improving the simulation of precipitation in the MMF, and the cloud-resolving model embedded in each GCM column further helps to boost precipitation rate.

Plain Language Summary Massive thunderstorms contribute a large proportion of warm season rainfall over the central United States. Previous studies have shown that the Multiscale Modeling Framework (MMF), which embeds a cloud-resolving model (CRM) into each global climate model grid column to simulate convection, provides a promising tool for simulating massive thunderstorms in the Tropics. However, it is unclear whether the MMF can simulate similar thunderstorms in midlatitudes such as in the central United States. Therefore, this study compares the MMF simulations with detailed available observations over the central United States. We find that the commonly used MMF with 2°-host-GCM (~200 km) grid spacing has difficulty in reproducing the observed rainfall because the host-GCM grid spacing is too coarse to capture the mesoscale circulations (at scales of approximately tens of kilometers) that are important for triggering the convection. When the host-GCM-grid spacing is reduced to a quarter degree (~25 km), the model succeeds to trigger the convection, so the rainfall simulation is improved. This study shows the importance of better representation of mesoscale circulations in models for predicting massive thunderstorms.

1. Introduction

Rainfall from mesoscale convective systems (MCSs) contributes up to 70% of warm season precipitation in the central United States (Fritsch et al., 1986; Laing & Fritsch, 1997; Haberlie & Ashley, 2019; Feng et al., 2019), and they often lead to dangerous flash flooding (Schumacher & Johnson, 2006; Stevenson & Schumacher, 2014). In addition, more frequent and stronger long-lived MCSs have been found to be responsible for the increasing trend in springtime total and extreme rainfall in the central United States over recent decades (Feng et al., 2016). Therefore, accurate representation of the MCSs and their resulting precipitation in climate models is crucial for predicting future extreme rainfall change over the United States.
Traditional global climate models (GCMs) have a common long-standing issue of being unable to simulate midlatitude warm season MCSs (Dai et al., 1999; Ghan et al., 1996; Lee et al., 2007). GCMs usually show a persistent summer warm and dry bias over the central United States (Cheruy et al., 2014; Klein et al., 2006; Lin et al., 2017; Morcrette et al., 2018). The model bias is often linked to the convective parameterizations that misrepresent or totally miss the mesoscale processes characterizing MCSs (Moncrieff & Liu, 2006; Van Weverberg et al., 2012). Many models use rather ad hoc criteria for the deep convection triggering (Randall et al., 2016;Suhas & Zhang, 2014). Conventional parameterizations unrealistically represent the coupling between cumulus processes and the low-level environment (Randall et al., 2016;Yano et al., 2014). They also fail to represent the upscale effects associated with the evolution from the cumulonimbus into mesoscale systems and subsequent interaction with large-scale dynamics (Moncrieff et al., 2012). They do not represent the important dynamics (e.g., wind shear effects) that control the convective organization and neglect the mesoscale circulations associated with large convective systems (Donner, 1993; Mrowiec et al., 2012). Therefore, mesoscale convective organization is structurally absent from current traditional GCMs. As a result, most GCMs cannot capture strong precipitation events and propagating episodes of convection (Kooperman et al., 2014; Lin et al., 2017), leading to uncertainty in the simulated projection of extreme precipitation change in the future climate.

Different from the traditional GCMs, the multiscale modeling framework (MMF), which bypasses the convection parameterization and explicitly resolves cellular convection, has shown some advantages in simulating the spatiotemporal structure of the diurnal scale of precipitation (Pritchard & Somerville, 2009a, 2009b) as well as MCS-like propagation behaviors in Summer in the central United States (Elliott et al., 2016; Kooperman et al., 2013;Pritchard et al., 2011). Using an MMF with a host GCM (Community Atmosphere Model, CAM3.0) at T42 horizontal spacing (2.8° × 2.8°), Pritchard and Somerville (2009a, 2009b) found broad improvements in the simulated diurnal variability compared to the standard CAM3.0. However, their analysis did not capture the propagating diurnal precipitation in the central United States. Interestingly, Pritchard et al. (2011) reported that the MMF of CAM3.5 at 1.9° × 2.5° host-grid spacing can reproduce the nocturnal and eastward MCS propagation signal in the atmospheric heating rate over the central United States. The simulated MCSs showed spatial scales, phase speeds, and propagation speeds similar to nature. Later, Kooperman et al. (2013) further confirmed the finding of Pritchard et al. (2011) by examining the simulations of different versions of MMF based on an empirical orthogonal function analysis of long-wave cloud forcing. These studies showed that the MCS-like signals could be detected from the MMF-modeled atmospheric heating rate or long-wave cloud forcing, suggesting that the MMF could be a promising tool to simulate the MCSs over the central United States. However, capturing some MCS-like signals does not mean that the model simulates realistic processes that initiate MCSs and their precipitation for the correct dynamical/physical reasons. There is no process-based study yet that evaluates MMF-simulated precipitation resulting from MCSs in detail. Therefore, it is unclear whether the MMF has the ability to capture the MCS-associated precipitation for the right reasons over the central United States.

To fill this gap, this study examines the MCS-associated rainfall simulated in a CAM5-based MMF with nudging and evaluates the model performance against observations at the level of individual MCS events. Our goals are to evaluate how well the prototype MMF, which uses roughly 2° host-grid spacing, can simulate the MCS-associated precipitation over the central United States and to understand the reason for model-observation discrepancies. The impact of host-model resolution is also investigated using simulations nudged toward the same reanalysis data at different resolutions. We compare the simulations against the available radar-based precipitation data, National Centers for Environmental Prediction North American Regional Reanalysis (NARR) data, and high-resolution Weather Research and Forecast (WRF) model simulations. This paper describes the MMF model and setup in section 2 and the individual MCS events in section 3, followed by the results in section 4. Section 5 presents the summary and discussion.

2. MMF Model and Simulation Setup

The MMF model used in this paper is the superparameterized version of CAM5.3 (Lin et al., 2018; Wang et al., 2011). The host model, CAM5.3, uses the finite volume dynamic core with 30 vertical levels. Embedded inside each GCM column, a two-dimensional cloud-resolving model (CRM), the System for Atmospheric Modeling (Khairoutdinov & Randall, 2003), replaces the conventional moist physics,
convective cloud, turbulence, and the boundary layer parameterization in CAM5.3. The CAM5 radiative transfer scheme Rapid Radiative Transfer Model for GCMs (RRTMG) is applied to each CRM column, using 1 or 0 of cloud fraction at each CRM grid. The CRM has 32 grid cells horizontally and 28 layers vertically; the horizontal grid spacing is 4 km; and the vertical layers coincide with the lowest 28 CAM levels. The CRM time step is 20 s. CAM5 provides the CRM large-scale forcing (dynamics and thermodynamics tendencies), while the CRM returns the heating and moisture tendency due to the CRM physics to the CAM5, without any momentum feedback. The 128-km CRM domain assumes flat topography, homogeneous surface conditions based on conditions in the host CAM5 grid cell, and uses periodic lateral boundary conditions. Therefore, the MMF does not resolve subgrid topography; each CRM within its host CAM grid cell does not directly interact with the CRMs in the neighboring CAM grid cells, although they interact indirectly through feedbacks on CAM grid cells.

We perform three MMF simulations with different host grid spacings: approximately 2°, 1°, and 0.25°, each using the same CRM setup. For the sake of brevity, hereafter we refer to these three simulations as MMF_2°, MMF_1°, and MMF_0.25°, respectively. We use the MMF_2° simulation as the control run, because most previous MMF studies have used 2° host GCM-grid spacing (Tao & Chern, 2017 and reference therein). In addition, we perform two traditional CAM5.3 simulations with 2° and 0.25° GCM-grid spacing, respectively, in which we do not use the CRM, but rather the traditional moist physics, convective cloud, turbulence, and boundary layer parameterizations in CAM5.3. We refer these two simulations as CAM5_2° and CAM5_0.25°.

All simulations are performed with prescribed monthly climatological sea surface temperatures and nudged toward the fifth generation of European Centre for Medium-Range Weather Forecasts atmospheric reanalyses of the global climate (ERA5) reanalysis horizontal winds (i.e., U and V) using a 6-h relaxation timescale. The nudging is applied to all vertical levels in the model. The ERA5 data set (Copernicus Climate Change Service [2017]: ERA5. Copernicus Climate Change Service Climate Data Store, date of access: November 2018 to February 2019, https://cds.climate.copernicus.eu/cdsapp#!/home) is provided every hour on a 30-km horizontal grid and it is regridded to the host-GCM grid at each resolution. The regridding ensures that each simulation is constrained toward similar large-scale flow conditions while simultaneously providing the small-scale flow details that are possible at the resolution of each simulation. For example, with the regridding, the 0.25° simulations will have the winds at the scale of 0.25°. This experimental setup allows us to investigate the effects of resolving different spatial scales of winds on the precipitation simulation within the model. All simulations are initialized with the atmospheric state variables at 1 May 2011 0 UTC obtained from the ERA5 data set. The initial cloud and aerosol fields are obtained from a separate 1° MMF simulation that runs from 1 January to 31 May 2011. All simulations are run for 1 month (May of 2011) due to the high computational cost of MMF simulations. Note that the computational cost of the MMF simulation is over 100 times higher than the traditional GCM simulation, and the MMF_0.25° simulation is about 26 times more expensive than the MMF_1° simulation.

In this study we focus in May 2011 during which the Midlatitude Continental Convective Clouds Experiment (MC3E) (Jensen et al., 2016) took place. The MC3E was supported by both the U.S. Department of Energy Atmospheric Radiation Measurement user facility and National Aeronautics and Space Administration’s Global Precipitation Measurement mission ground validation program in north-central Oklahoma. In May 2011, several strong MCS events, starting on 1, 11, 20, and 23–26 May, passed over the central United States (Jensen et al., 2016).

### 3. Event Overview and Observational Data Sets

The 1 May event is characterized by an upper-level low pressure over the north-central United States near Canada, with low-level northwesterly winds over the northern Great Plains but southerly winds over the south-central United States (Figures 1a and 1b). As a result, there is a large frontal system across the south-central United States extending from Texas to Illinois. Convection initiated along the warm sector of the frontal system in Arkansas around 0 UTC and later in Texas around 8 UTC. Several intense MCSs subsequently developed along the front and propagated northeastward, producing heavy precipitation across the Southern Great Plain (SGP) region. As the cold front pushed southeastward and the pressure gradient was increased, the heavy precipitation band became elongated, stretching from central Texas to Indiana.
Figure 1. (a) Radar reflectivity (shaded; dBZ) obtained from the NEXRAD, and 300 hPa geopotential height (solid black lines) obtained from the NARR at the beginning stage of the 1 May MCS event. The magenta text shows the abbreviated U.S. state names: TX stands for Texas, LA for Louisiana, MS for Mississippi, AK for Arkansas, OK for Oklahoma, MO for Missouri, IL for Illinois, IN for Indiana, and TN for Tennessee. (b) Equivalent potential temperature (shaded) and horizontal winds at 900 hPa from the NARR at the beginning stage of the 1 May MCS event. The magenta solid line denotes the approximate location of the front. (c and d) The 11 May MCS event. (e and f) The 20 May MCS event. (g and h) The 25 May MCS event.
Precipitation finally exited the SGP region by the end of 3 May as the upper-level low-pressure system moved to the northeastern United States (see the Animation SI in the supporting information SI).

For the 11 May event, severe convective systems were initiated by a cold front/dry line early in the day and propagated across the Texas-Oklahoma Panhandle region (Figures 1c and 1d). More convection was initiated along the cold front as it progressed eastward, and subsequently grew upscale into a quasi-linear MCS around 16 UTC. Finally, the MCS developed a trailing stratiform precipitation region as it propagated eastward across Oklahoma and Texas between 18 and 19 UTC (Jensen et al., 2016).

The 20 May event had a deep, upper-level low situated over the western portion of the Colorado Plateau. This low moved across the central and southern Rockies into the central and northern plains (Figure 1e). A low-level jet located over the southern Plains drew warm and moist air from the Gulf of Mexico (Figure 1f), with a low-level convergence zone along the Texas Panhandle, western Oklahoma, and Kansas. The squall line evolved from two convective lines during the developing stage between 1 and 6 UTC: a northern segment located in Kansas and a southern segment located in western Oklahoma and northern Texas. The two lines began to converge around 6:30 UTC, the southern line dominated, and the system developed into a quasi-linear MCS with a leading line and an extensive region of trailing stratiform precipitation (Fan et al., 2017; Han et al., 2019). As the low-pressure system moved eastward, the MCS also propagated eastward along with the cold front (see the Animation S2 in the SI).

The 23 May event formed near the intersection of a stationary front and an easterly outflow boundary. Convection was initiated to the southwest of the SGP site at around 21 UTC on 23 May and rapidly intensified 1 h later. The system propagated southeastward and dissipated at around 4 UTC on 24 May (Fan et al., 2017). Strong precipitation at the SGP from the 24 May and 25 May events was associated with the fronts passing over the SGP region and moving toward the east (Figures 1g and 1h).

To evaluate the MMF model, we use the National Severe Storms Laboratory (NSSL) multisensor Q2 precipitation data (Zhang et al., 2011), NARR reanalysis data (https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html), and a high-resolution WRF simulation (Skamarock et al., 2008). The Q2 precipitation data...
combines Next-Generation Radar Quantitative Precipitation Estimate and surface rain gauge network data. The Q2 precipitation data used in this study incorporate data from rain gauge network for bias correction, which is provided at 1 km and 1-hourly resolution. We use horizontal winds (U and V), water vapor, and atmospheric temperature from the NARR reanalysis data as proxies for large-scale environment observations.

The WRF simulation used for comparison with the MMF simulations was run continuously from 1 May to 1 June 2011 for the MC3E period. A nested domain was used with the innermost domain extending from western Colorado to central Virginia and from the Gulf Coast to South Dakota with grid spacing of 1.8 km. This is nested within a mother domain with 5.4-km grid spacing that extends from Nevada to the Atlantic Coast and from central Mexico to Canada. Fifty-one vertical levels were used with a model top at 70 hPa. The 1.8-km grid spacing was chosen to have sufficient resolution on the innermost domain to be able to turn off the cumulus parameterization and explicitly simulate deep convection. The outer domain used the newer version of the Tiedtke deep convection parameterization available in WRF that is similar to that used in the European Centre for Medium-Range Weather Forecasts model (Tiedtke, 1989). The remaining physics choices matched between the nested domains. The other physics schemes used in the WRF simulation are listed in Table S1. Lateral boundary and initial conditions were taken from the Global Forecast System analyses with a 10-point buffer zone used around the outermost domain edge. By comparing with the Next-Generation Radar radar reflectivity (Figure S9), we find that the WRF simulation can successfully capture the MCS initiation and development. Therefore, we use the WRF simulation as a reference for evaluating MMF simulations.

4. Results

In this section, we first provide an overview of the MMF simulation results and their comparison with observations. Then we examine the MMF model performance in simulating individual MCS events and explore the dynamical/physical reasons for the model-observation differences in precipitation. Last, we present the results from the CAM5 simulations.

Figure 3. Time series of hourly-mean precipitation rates averaged over the SGP area shown in the red box of Figure 2. Obs stands for the NSSL Q2 precipitation data. The numbers in parenthesis represent the box-averaged values of monthly-mean precipitation rates.
4.1. MMF Simulation Result Overview

Figures 2a and 2b show the monthly-mean precipitation rate for May 2011 over the continental United States from the NSSL Q2 observations and the MMF_2° simulations. Clearly, the MMF_2° simulation substantially underpredicts the precipitation rate over the SGP area. The Q2 data show a large amount of monthly-mean precipitation (stronger than 0.3 mm/h) over Oklahoma, Missouri, Arkansas, and Northern Texas, while the MMF_2° simulation predicts very little precipitation (primarily less than 0.1 mm/h) over those regions. To further illustrate the model dry bias, we choose an area over the SGP region (the red box in Figure 2) to examine the time series of hourly precipitation averaged over the region (Figure 3). Consistent with what are shown in Figures 2a and 2b, Figure 3a also shows that MMF_2° simulation underestimates the precipitation rate during the entire month. The NSSL Q2 data show a box-averaged monthly-mean precipitation rate of 0.19 mm/h, nearly 3 times higher than the value from the MMF_2° simulation (0.07 mm/h). There are several major MCS events passing over the SGP area with a start dates on 1 May, 11 May, 20 May, and 23–26 May. However, MMF_2° significantly underestimates all these events and barely simulates the 11 May and 23–26 May events.

The monthly-mean (May) precipitation rate from simulations of reduced host-grid spacing (MMF_1° and MMF_0.25°) are shown in Figures 2c and 2d. It is clear that reducing the host-GCM-grid spacing increases the mean precipitation rate and thus reduces the model-observation discrepancy, particularly over the SGP area. The time series of hourly precipitation rate over the SGP area (Figure 3b) further illustrates that the finer host-GCM-grid spacing reduces the MMF-simulated precipitation bias at the hourly scale. Among the three simulations, the MMF_0.25° simulation agrees best with the observation. Specifically, the
precipitation during 1–3 May is enhanced, the precipitation peaks on 12 and 20 May are better reproduced, and the strong precipitation events during 23–26 May are also simulated best. However, there are still some deficiencies compared to the observation: a much weaker peak on 21 May and unobserved precipitation peaks on 18–19 May.

To investigate the reasons for the differing performances between simulations for these events, we examine each event in detail in the following sections. We focus on the 1 and 20 May events, as the former represents underestimation of precipitation by the MMF_2° simulation, while the latter represents a failure of the model to initiate the convection and precipitation. The 11 and 23–26 May events have similar MCS initiation and evolution mechanisms as the 20 May event; therefore, they are only described briefly in the paper but with full figures in the SI.

### 4.2. Model Underestimation of Precipitation: 1 May Event

Figures 4a and 4b, and 5a and 5b show the geopotential height at 500 hPa, horizontal winds at 900 hPa, and surface precipitation over the eastern half of the United States from the observations and the MMF_2° simulation at 3 UTC and 12 UTC on 1 May 2011. The two snapshots correspond to the initiation and mature stages of this MCS event, respectively.

Compared to the observations, the MMF_2° simulation predicts similar precipitation patterns but with much weaker intensity, even though the model reproduces the location of the synoptic frontal system. We understand the 1 May event is close to the model initial time. However, a separate simulation that starts from 1 January 2011 shows similar results, indicating the simulation of 1 May event is not sensitive to the initial time. To explore the reasons for the weaker precipitation predicted in the MMF_2° simulation, we further...
compare the strength of the frontal system (defined as the water vapor gradient across the front) and Convective Available Potential Energy (CAPE) between the observations and simulation (Figures 6a and 6b, and 7a and 7b). The weaker water vapor gradient across the front clearly reflects the weaker front simulated in the model (Figures 6a and 6b). To illustrate the water vapor gradient difference, we calculate the maximum meridional gradient over the box (32°–38°N, 100°–95°W, see the red box in Figures 6a and 6b) across the front. Over the box, the maximum value of the simulated gradient is 50% smaller than that obtained from the NARR data. The vertical cross section of winds across the front boundary further shows the stronger frontal lifting in the NARR than simulated in the MMF_2° simulation (Figures 8a and 8b). In addition, the model also shows smaller CAPE ahead of the front than observed (Figure 7b), which can be explained by the dryer atmosphere simulated in the model (figure not shown). The weaker front and smaller CAPE explain the simulated underestimate of precipitation.

Figures 4c and 4d, and 5c and 5d show the spatial maps of hourly precipitation simulated from MMF_1° and MMF_0.25° simulations. By comparing to the MMF_2° simulation, one can notice that the MMF performance in simulating the precipitation improves as the host-GCM-grid spacing becomes smaller. The MMF_1° predicts stronger precipitation than the MMF_2° as the MCS develops; the MMF_0.25° predicts the most realistic spatiotemporal evolution of precipitation. Comparisons of CAPE among these three simulations show that reducing the GCM-grid spacing causes a decrease in the CAPE values (Figures 7c and 7d). However, reduced grid spacing leads to a stronger water vapor gradient and thus the stronger frontal system as well. The MMF_0.25° shows the strongest water vapor gradients across the front (Figure 6d). Again, we calculate the meridional water vapor gradient over the box (32°–38°N, 100°–95°W, see the red box in Figures 6c and 6d) across the front. We find that the maximum gradient over the box in the MMF_0.25° simulation is 3 times higher than that in the MMF_2° simulation. The vertical cross sections of water

Figure 6. The 900-mb water vapor (Q) distributions over the SGP area from (a) the NARR reanalysis data, (b) the MMF_2° simulation, (c) the MMF_1° simulation, and (d) the MMF_0.25° simulation. The solid black dot lines denote the line along which the vertical cross-section plots are made in Figure 8. The red box represents the area over which we calculate the maximum meridional water vapor gradient.
Figure 7. Surface-based Convective Available Potential Energy (CAPE) calculated from the NARR reanalysis data (a) and the difference of CAPE between the NARR data and the MMF_2° simulation (b), between the MMF_1° and MMF_2° simulations (c), and between the MMF_0.25° and MMF_2° simulations (d). Data are coarsened to 2° for the calculations of differences.

Figure 8. Vertical cross sections of water vapor mixing ratio (color shading), potential temperature (contour lines in pink; °C), 900-hPa water vapor gradient (dot lines in magenta), and wind vectors (vertical and zonal wind component) along the black dotted lines in Figure 6 from (a) the NARR data, (b) MMF_2°, (c) MMF_1°, and (d) MMF_0.25° simulations at 3 UTC on 1 May 2011. For the purpose of better visualization, the vertical wind component is multiplied by a factor of 1000.
vapor mixing ratio and winds further illustrate that the 0.25° model produces the strongest water vapor gradient and rising motion along the frontal boundary (Figure 8), leading to the strongest precipitation. However, it should be noted that the MMF_0.25° simulation still shows some differences compared to the NARR data. For instance, the MMF_0.25° simulation still has weaker vertical winds, the horizontal moisture gradient is exaggerated, and the low-level moisture does not penetrate as high as in the NARR data.

4.3. Failure in Simulating Convective Initiation and Precipitation: 20 May Event

For the 20 May 2011 case, the MMF_2° simulation captures the large-scale low-pressure system and the low-level winds due to the wind-nudging configuration. However, the model fails to initiate the convection near western Oklahoma and thus produces little precipitation over the SGP (Figures 9a and 9b, and 10a and 10b). To explore the reasons for the MMF model failure of convective initiation, we examine the WRF simulation that successfully reproduces the convection initiation over the Texas/Oklahoma Panhandle and the further upscale development to an MCS (Figure 11). The WRF simulation shows a strong dryline located over the western Texas/Oklahoma Panhandle (Figure 11). Along the dryline, there is a sharp and strong low-level convergence line lifting the moist air upward to overcome the temperature inversion above the surface that inhibits convective initiation (not shown), and several supercell thunderstorms are initiated and subsequently propagate slowly eastward. Previous studies have demonstrated that the interactions between the dryline and cold front are effective mechanisms for initiating deep moist convection (e.g., Koch & McCarthy, 1982; Qin & Chen, 2017; Weiss & Bluestein, 2002). A dryline usually results from the confluence of dry continental westerlies and moist maritime southerlies; in the United States, it often forms on the lee-side of the Rocky Mountains. The dryline can help trigger convection because (1) the dryline boundary is often associated with locally enhanced near-surface convergence, (2) the shallow moist air east of the dryline promotes instability, and (3) there exists a secondary vertical circulation across the dryline because of the difference in surface sensible heating and the heat capacity of the air between two sides of the dryline.

Figure 9. The same as Figure 4 but for 21 UTC on 19 May 2011.
The WRF simulation shows a typical dryline structure in Figure 11, which has a strong moisture gradient and a distinct near-surface convergence line in the western Texas/Oklahoma Panhandle. In contrast, the MMF_2° simulation fails to simulate the convergence seen in the WRF simulation (Figures 11 and 12); therefore, convection cannot be triggered. It should be noted that under the current setup in the prototype MMF, CRMs within each GCM grid feel the momentum only from the GCM grid, but they do not feed momentum changes from the small-scale motions back to the GCM. And, the periodic, 2-D CRM setup makes the embedded CRM model incapable of simulating the sub-GCM-grid 3-D...
convergence. With the 2° host-grid spacing, the model thus cannot capture this small-scale convergence line as shown in the WRF simulation. Moreover, the uniform topography used within the CRM domain precludes the terrain impacts on the dryline formation that are important for the convection initiation. As a result, although the MMF_2° model has many CRM cells in each GCM column, the MMF cannot properly simulate the mesoscale dryline formation and the resulting convection.

When the host-grid spacing is reduced to 0.25°, the MMF model produces persistent rain over southwestern Texas throughout the whole day (Figures 9, 10, and Animation S2 in the SI). A convective line is triggered and moves across central Texas from south to north at around 9 UTC (Figure 10d), which later grows upscale to an MCS-like system and propagates eastward. Clearly, the MMF_0.25 simulation succeeds in triggering the convection, although the timing and position of the convective line are offset to the east compared to the observation. The analysis of CAPE shows that the CAPE over central Texas in the MMF_0.25° simulation is smaller than in the MMF_2° simulation (Figure 13d). This is because convection and precipitation occur in the upstream area of the low-level jet over southern Texas (see Animation S2 in the SI), which consumes water vapor in the air and reduces the instability and thus the CAPE. Despite the lower CAPE, the MMF_0.25° still succeeds in initiating the convection due to much stronger low-level convergence than

![Figure 12](image12.png)

**Figure 12.** The 900-hPa winds and divergence calculated from the MMF_2° (a), MMF_1° (b), and MMF_0.25° (c) simulations.

![Figure 13](image13.png)

**Figure 13.** The same as Figure 7 but for prestorm environments of 20 May 2011 event.
the other two simulations (Figure 12). Therefore, for dryline initiated convection over the SGP area, having sufficient resolution to capture the mesoscale dynamics is very important.

Similar to the 20 May event, the convection on 11 and 23–26 May also initiated over the SGP and subsequently propagated eastward (Figure S1, S2, S5, S6, and Animation S3 and S4 in the SI). Again, the MMF_2° simulation fails to initiate these convective events as observed. Similarly, the evidence implies that this is also because the 2° host-GCM grid is too coarse to simulate the mesoscale dryline/frontal systems that are important for triggering the convection. We expect that reducing the host-GCM grid spacing will help resolve the mesoscale dryline/frontal convergence and thus the triggering of convection over the SGP area. As expected, the MMF_0.25° simulation performs much better than the other two simulations in capturing the convection triggering and the precipitation intensity for the 11 and 23–26 May cases. The improvements are more significant compared with those in the 1 and 20 May cases. The MMF_0.25° simulates not only...
stronger convergence (Figures S4 and S8) but also higher CAPE than the two coarser simulations (Figures S3 and S7). This is different from the 1 and 20 May cases where we see stronger convergence but similar or lower CAPE in the MMF_0.25° simulations. Both stronger low-level convergence and higher CAPE favor convective initiation and stronger convection, leading to much improved model performance in simulating the precipitation for these two cases.

4.4. Traditional CAM5 Simulations Without Using the CRM

So far we have shown that reducing the host-grid spacing helps the MMF capture the MCS-associated precipitation, but one may wonder whether the traditional GCMs without using the CRM achieve similar results as the GCM-grid spacing is reduced. In other words, can the CRM embedded in the CAM5 column further help the model capture the intense precipitation associated with MCSs? To answer this question, we carry out two standard CAM5 simulations using a traditional cumulus parameterization: CAM5_2° and CAM5_0.25° with 2° and 0.25° GCM-grid spacing, respectively.

Figure 14 shows the spatial map of monthly-mean precipitation rates and time series of hourly-precipitation rates over the SGP area from these two simulations. Similar to what MMF simulations have shown, reducing the GCM-grid spacing drastically increases precipitation rates overall (by up to a few times for the peak rain rates of three of the four MCSs case over the SGP area) and thus improves the CAM5 performance in simulating the precipitation. For the relatively large rain rates (greater than 1.5 mm/h), the SGP box-averaged monthly-mean convective precipitation rate for CAM5_2° is 1.85 mm/h, while it is increased to 2.89 mm/h for the CAM5_0.25° simulation. However, the CAM5_0.25° simulation still simulates weaker precipitation rates compared to the MMF_0.25° (see Figure 3), which predicts a SGP box-averaged monthly-mean convective precipitation of 3.49 mm/h. These results indicate that increasing resolution plays a dominant role in improving the simulation of precipitation in the MMF_0.25°, and the CRM embedded in each GCM column further helps to achieve a higher rain rate. Closer examination of individual MCS events also confirms this conclusion. For instance, while the CAM5_0.25° simulation can reproduce the convection-like precipitation line across Texas for the 20 May case (Figure 15), the intensity of precipitation is weaker than the MMF_0.25° and the observation (Figure 10).

5. Summary and Discussion

In this paper, we evaluate the MMF-simulated MCS-associated precipitation in May 2011 during the MC3E field campaign. Different from previous MMF studies, we examine the MCS-associated precipitation at the level of individual MCS events by comparing with the 3-hourly environmental variables provided by NARR reanalysis data, the 1-hourly NSSL Q2 precipitation data, and the high-resolution WRF simulation. This detailed analysis allows us to show that the coarse host-GCM-grid MMF simulation (2° grid spacing) fails to initiate the convection in three out of four MCS events during the period, because the model cannot capture the mesoscale dryline/frontal systems that trigger the convection. This failure occurs in spite of constraining the model flow via nudging. In contrast, in the 1 May case, where the MCS is driven by the large-scale frontal system, the model succeeds in triggering the convection. However, the simulated precipitation is much weaker than observed due to the weaker intensity of the simulated front. By reducing the host-GCM-grid spacing, the model-observation precipitation deficiency is reduced by 23%. The nudged simulation with 0.25° host-GCM-grid spacing successfully triggers the convection in all four MCS cases and captures the precipitation intensity significantly better (the bias is reduced by 31%) than the model configuration with the 2° host-GCM-grid spacing. Yet the timing and position of convection triggering in the model with 0.25° host-GCM-grid spacing still show some discrepancies compared to observations. By performing the traditional CAM5 simulations that do not have the embedded CRMs, we further confirm that having finer grid spacing is key for resolving the mesoscale dynamics and thus for capturing MCS-like precipitation. We also demonstrate that explicitly resolving the cloud physics/motions in the 2D CRM is superior to the traditional cumulus parameterization in capturing the precipitation intensity.

Previous studies show that the MMF with the coarse host-GCM grid is able to capture MCSs in the Tropics (Tao & Chern, 2017; Randall et al., 2016). However, our study shows the MMF model has difficulty in simulating MCS-associated precipitation in midlatitude continental conditions during spring where most MCSs were supported by strong baroclinic forcing (Feng et al., 2019; Song et al., 2019). The different model behaviors reflect the different mechanisms driving the MCSs between tropical and midlatitude regions. MCSs
over the tropical regions mostly grow upscale from surface heating thermodynamically triggering convection, while the triggering of convection over the midlatitudes springtime is driven by dynamics, such as by fronts and drylines. The current prototype MMF with a 2° host-GCM grid is too coarse to simulate the intensity of the large-scale frontal systems and resolve mesoscale dynamics such as drylines. Although the embedded 2-D CRMs resolve the cloud-scale heating and drying, they cannot simulate mesoscale convergence and do not feed back subhost-GCM-scale momentum changes to the GCM grid. In addition, the prototype MMF is incapable of simulating the sub-GCM-grid topographic effects on the convection due to the uniform topography used within the CRM domain. Thus, the CRMs cannot properly capture the salient physics necessary to maintain and propagate midlatitude MCSs. Reducing the host-GCM-grid spacing is one of the ways to better resolve the large-scale and mesoscale dynamics and topographic variations for midlatitude MCS simulations during the spring season. Alternatively, the employment of the Quasi-3D (Q3D) MMF, which consists of two perpendicular sets of channels containing a local 3D array of grid points, may also overcome some of the limitations (Jung & Arakawa, 2010).

This paper highlights the importance of resolving mesoscale dynamics in simulating midlatitude MCSs during spring. The mesoscale front/drylines play a key role in initiating convection, which can further grow to MCSs. This poses a great challenge for simulating MCSs within GCMs. The traditional GCM generally lacks a parameterization scheme that can represent deep convection in the form of MCSs. Comparatively, the prototype MMF has its own limitation due to the two-dimensionality and periodic boundary conditions of the embedded CRMs. As shown in this paper, the MMF with 2° host-GCM-grid spacing does not resolve any of the mesoscale dynamics in most cases, while the MMF with 0.25° host-GCM-grid spacing partially resolve them once the system has grown up scale. In the present case, the mesoscale convergence zones are being forced into the MMF with 0.25° host-GCM-grid spacing, which ensures that the necessary physical processes are captured to see how the embedded CRMs respond. This essentially points toward the potential of the MMF to truly capture MCSs. However, it is worth noting that the simulation with 0.25° host-GCM-grid spacing performs better in resolving small-scale dynamics not only because it has the finer host-GCM-grid spacing but also because it is nudged to the winds at 0.25°, which is very close to the resolution of ERA-5 reanalysis. In addition, the 6-h nudging timescale used in this work is shorter than the typical MCS lifetime. That might put too much constraint on the MCS development. Thus, future work is needed to determine how well free-running high-resolution MMF configurations can capture midlatitude MCSs when the model flow is unconstrained. Investigating how resolving topography variations within the CRM domains would help the MMF model simulate MCSs can be an interesting future work. Further, summer MCSs in this region often occur under weak baroclinic forcing with favorable thermodynamic environments (Feng et al., 2019; Song et al., 2019). Future work similar to this study is needed to examine how well the MMF can simulate observed summer MCSs. In the long term, global CRMs are expected to resolve mesoscale dynamics, but at present, these global models are impracticable beyond extremely short simulations. Alternatively, regional models at kilometer-scale horizontal grid spacing can be used to simulate MCSs at a regional scale (e.g., Prein et al., 2017; Feng et al., 2018).

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References
Cheruy, F., Dufresne, J. L., Hourdin, F., & Ducharne, A. (2014). Role of clouds and land-atmosphere coupling in midlatitude continental summer warm biases and climate change amplification in CMIP5 simulations. Geophysical Research Letters, 41, 6493–6500. https://doi.org/10.1002/2014GL061145
Dai, A. G., Giorgi, F., & Trenberth, K. E. (1999). Observed and model-simulated diurnal cycles of precipitation over the contiguous United States. Journal of Geophysical Research, 104, 6377–6402.
Donner, L. J. (1993). A cumulus parameterization including mass fluxes, vertical momentum dynamics, and mesoscale effects. Journal of the Atmospheric Sciences, 50(6), 889–906. https://doi.org/10.1175/1520-0469(1993)050<0889:ACPIMM>2.0.CO;2
Elliot, E. J., Yu, S., Kooperman, G. J., Morrison, H., Wang, M., & Pritchard, M. S. (2016). Sensitivity of summer ensembles of fiedling superparameterized U.S. mesoscale convective systems to cloud resolving model microphysics and grid configuration. Journal of Advances in Modeling Earth Systems, 8, 634–649. https://doi.org/10.1002/2015MS000656
Fan, J., Han, B., Varble, A., Morrison, H., North, K., Kollias, F., et al. (2017). Cloud-resolving model intercomparison of an MCE3 equalline case: Part I—Convective updrafts. Journal of Geophysical Research: Atmospheres, 122, 9351–9378. https://doi.org/10.1002/2017JD026626
Feng, Z., Houze, R. A., Leung, R., Song, F., Hardin, J., Wang, J., et al. (2019). Spatiotemporal characteristics and large-scale environments of mesoscale convective systems east of the Rocky Mountains. Journal of Climate, 32(21), 7303–7328. https://doi.org/10.1175/jcli-d-19-0137.1
Feng, Z., Leung, R. R., Hagos, S., Houze, R. A., Burleyson, C. D., & Balaguru, K. (2016). More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. Nature Communications, 7, 13429. https://doi.org/10.1038/ncomms13429
Feng, Z., Leung, L. R., Houze, R. A. Jr., Hagos, S., Hardin, J., Yang, Q., et al. (2018). Structure and evolution of mesoscale convective systems: Sensitivity to cloud microphysics in convection-permitting simulations over the United States. Journal of Advances in Modeling Earth Systems, 10, 1470–1494. https://doi.org/10.1002/2018MS001395

Fritsch, J. M., Kane, R. J., & Chellius, C. R. (1986). The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. Journal of Climate and Applied Meteorology, 25(10), 1333–1345. https://doi.org/10.1175/1520-0442(1986)025<1333:TCDMAW>2.0.CO;2

Ghan, S. J., Bian, X., & Corsetti, L. (1996). Simulation of the Great Plains low-level jet and associated clouds by general circulation models. Monthly Weather Review, 124, 1388–1408.

Khairoutdinov, M. F., & Randall, D. A. (2003). Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. Journal of the Atmospheric Sciences, 60(4), 607–625. https://doi.org/10.1175/1520-0469(2003)060<0607:CRMOTA>2.0.CO;2

Klein, S. A., Jiang, X., Boyle, J., Malyshev, S., & Xie, S. (2006). Diagnosis of the summertime warm and dry bias over the U.S. Southern Great Plains in GFDL climate model using a weather forecasting approach. Geophysical Research Letters, 33, L18805. https://doi.org/10.1029/2006GL027567

Kooperman, G. J., Pritchard, M. S., & Somerville, R. C. J. (2013). Robustness and sensitivities of Central U.S. summer convection in the superparameterized CAM: Multi-model intercomparison with a new regional EOF index. Geophysical Research Letters, 40, 3287–3291. https://doi.org/10.1002/Grl.50597

Kooperman, G. J., Pritchard, M. S., & Somerville, R. C. J. (2014). The response of US summer rainfall to quadrupled CO2 climate change in conventional and superparameterized versions of the NCAR community atmosphere model. Journal of Advances in Modeling Earth Systems, 6, 859–882. https://doi.org/10.1002/2013MS000306

Laing, A. G., & Fritsch, J. M. (1997). The global population of mesoscale convective complexes. Quarterly Journal of the Royal Meteorological Society, 123(538), 399–405. https://doi.org/10.1002/qj.49712353807

Lee, M.-I., Schubert, S. D., Suarez, M. J., Held, I. M., Lau, N. C., Ploshay, J. J., et al. (2007). An analysis of the warm-season diurnal cycle over the continental United States and northern Mexico in general circulation models. Journal of Hydrometeorology, 8(3), 344–366. https://doi.org/10.1175/JHM581.1

Lin, G., Ghan, S. J., Wang, M., Ma, P.-L., Easter, R. C., Ovchinnikov, M., et al. (2018). Development and evaluation of an explicit treatment of aerosol processes at cloud scale within a Multi-Scale Modeling Framework (MMF). Journal of Advances in Modeling Earth Systems, 10(7), 1670–1679. https://doi.org/10.1002/2018MS001287

Lin, Y., Dong, W., Zhang, M., Xie, Y., Xue, W., Huang, J., & Luo, Y. (2017). Causes of model dry and warm bias over central U.S. and impact on climate projections. Nature Communications, 8(1), 881. https://doi.org/10.1038/s41467-017-01040-2

Moncrieff, M. W., & Liu, C. H. (2006). Representing convective organization in prediction models by a hybrid strategy. Journal of the Atmospheric Sciences, 63(12), 3404–3420. https://doi.org/10.1175/JAS3812.1

Moncrieff, M. W., Waliser, D. E., Miller, M. J., Shapiro, G. A., & Caughey, J. (2012). Multiscale convective organization and the YOTC Virtual Global Field Campaign. Bulletin of the American Meteorological Society, 93, 1171–1187. https://doi.org/10.1175/BAMS-D-11-00233.1

Morcrette, C. I., Van Weverberg, K., Ma, H. Y., Ahlgriim, M., Bazile, E., Berg, L. K., et al. (2018). Introduction to CAUSES: Description of weather and climate models and their near-surface temperature errors in 5 day hindcasts near the Southern Great Plains. Journal of Geophysical Research: Atmospheres, 123, 2655–2683. https://doi.org/10.1002/2017JD027199

Mrowiec, A. A., Rio, C., Fridlind, A. M., Ackerman, A. S., Del Genio, A. D., Pauluis, O. M., et al. (2012). Analysis of cloud-resolving simulations of a tropical mesoscale convective system observed during TWP-ICOVE: Vertical fluxes and draft properties in convective and stratiform regions. Journal of Geophysical Research, 117, D19201. https://doi.org/10.1029/2012JD017759

Nesbitt, S. W., Cifelli, R., & Rutledge, S. A. (2006). Storm morphology and rainfall characteristics of TRMM precipitation features. Monthly Weather Review, 134(10), 2702–2721. https://doi.org/10.1175/Mwr2001.1

Plein, A. F., Liu, C., Ikeda, K., Bullock, R., Rasmussen, R. M., Holland, G. J. & Clark, M. (2017). Simulating North American mesoscale convective systems with a convection-permitting climate model. Climate Dynamics. https://doi.org/10.1007/s00382-017-3993-2

Pritchard, M. S., Moncrieff, M. W., & Somerville, R. C. J. (2011). Orogenic propagating precipitation systems over the United States in a global climate model with embedded explicit convection. Journal of the Atmospheric Sciences, 68(8), 1821–1840.

Pritchard, M. S., & Somerville, R. C. J. (2009a). Assessing the diurnal cycle of precipitation in a multi-scale climate model. Journal of Advances in Modeling Earth Systems, 1, 12. https://doi.org/10.3894/JAMES.2009.1.12

Pritchard, M. S., & Somerville, R. C. J. (2009b). Empirical orthogonal function analysis of the diurnal cycle of precipitation in a multi-scale climate model. Geophysical Research Letters, 36, L05812. https://doi.org/10.1029/2008GL036964

Qin, R., & Chen, M. (2017). Impact of a front-dryline merger on convection initiation near a mountain ridge in Beijing. Monthly Weather Review, 145, 2611–2633.

Randall, D., DeMott, C., Stan, C., Khairoutdinov, M., Benedict, J., Mccrory, R., et al. (2016). Simulations of the tropical general circulation with a multiscale global model. Meteorological Monographs, 56, 15–15.15. https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0001.1

Schumacher, R. S., & Johnson, R. H. (2006). Characteristics of U.S. extreme rain events during 1999–2003. Weather Forecasting, 21(1), 69–85. https://doi.org/10.1175/WAF9001.1
Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, et al. (2008). A description of the Advanced Research WRF version 3, 113 pp, NCAR Technical Note, NCAR/TN-475+STR, National Center for Atmospheric Research, http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf.

Song, F., Feng, Z., Leung, R., Houze, R. A., Wang, J., Hardin, J., & Homeyer, C. R. (2019). Contrasting spring and summer large-scale environments associated with mesoscale convective systems over the U.S. Great Plains. *Journal of Climate, 32*(20), 6749–6767. https://doi.org/10.1175/JCLI-D-18-0839.1

Stevenson, S. N., & Schumacher, R. S. (2014). A 10-year survey of extreme rainfall events in the central and eastern United States using gridded multisensor precipitation analyses. *Monthly Weather Review, 142*(9), 3147–3162. https://doi.org/10.1175/MWR-D-13-00345.1

Stimleth, J. I., Geleyn, J. F., Köhler, M., Mironov, D., Quaas, J., Soares, P., et al. (2014). Basic concepts for convection parameterization in weather forecast and climate models: COST action ES0905 final report. *Atmosphere, 6*(1), 88–147. https://doi.org/10.3390/atmos6010088

Yano, J.-I., Geleyn, J. F., Köhler, M., Mironov, D., Quaas, J., Soares, P., et al. (2014). Basic concepts for convection parameterization in weather forecast and climate models: COST action ES0905 final report. *Atmosphere, 6*(1), 88–147. https://doi.org/10.3390/atmos6010088

Zhang, J., Howard, K., Langston, C., Vasiloff, S., Kaney, B., Arthur, A., et al. (2011). National Mosaic and Multi-Sensor QPE (NMQ) system: Description, results, and future plans. *Bulletin of the American Meteorological Society, 92*(10), 1321–1338. https://doi.org/10.1175/2011BAMS-D-11-0047.1