Evaluation of Cumulus and Microphysics Parameterizations in WRF across the Convective Gray Zone

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ABSTRACT

This study evaluates the grid-length dependency of the Weather Research and Forecasting (WRF) Model precipitation performance for two cases in the Southern Great Plains of the United States. The aim is to investigate the ability of different cumulus and microphysics parameterization schemes to represent precipitation processes throughout the transition between parameterized and resolved convective scales (e.g., the gray zone). The cases include the following: 1) a mesoscale convective system causing intense local precipitation, and 2) a frontal passage with light but continuous rainfall. The choice of cumulus parameterization appears to be a crucial differentiator in convective development and resulting precipitation patterns in the WRF simulations. Different microphysics schemes produce very similar outcomes, yet some of the more sophisticated schemes have substantially longer run times. This suggests that this additional computational expense does not necessarily provide meaningful forecast improvements, and those looking to run such schemes should perform their own evaluation to determine if this expense is warranted for their application. The best performing cumulus scheme overall for the two cases studies here was the scale-aware Grell–Freitas cumulus scheme. It was able to reproduce a smooth transition from subgrid- (cumulus) to resolved-scale (microphysics) precipitation with increasing resolution. It also produced the smallest errors for the convective event, outperforming the other cumulus schemes in predicting the timing and intensity of the precipitation.

1. Background and introduction

Earth's atmosphere is a complex system comprising the nonlinear interaction and superposition of processes occurring on a large range of scales: from planetary waves, synoptic systems, secondary circulations, and mesoscale systems, down to turbulent eddies, cloud microphysics, and molecular diffusion. The mathematical description of these atmospheric processes in numerical weather prediction (NWP) models is often simplified depending on the model purpose, resolution, and focus (Coiffier 2011). The dynamical core solves the governing equations on a discrete grid, neglecting terms of approximated low significance (Warner 2010). Unresolved processes, such as radiation, deep and shallow cumulus convection, cloud microphysics, precipitation, and turbulence, affect the resolved scales through a

parameterized representation in NWP (Stensrud 2007; Warner 2010; Coiffier 2011; Stull 2017).

General circulation models (GCM) simulate the atmosphere often on a global scale at relatively coarse horizontal resolutions (about 25–100 km), where various processes unresolved at the given grid spacing must be parameterized, while regional models often contain nested higher-resolution domains and parameterize processes at scales of less than 10–50 km. Models using a grid spacing smaller than 4 km are generally considered convection permitting and do not rely on cumulus parameterization schemes following the assumption that the model is capable of resolving organized convection at this resolution (Weisman et al. 1997; Arakawa et al. 2011; Prein et al. 2015). Large-eddy simulations (LES) have such fine grid spacing (about 10–300 m) that large boundary layer eddies (in addition to cumulus convection) are explicitly resolved but the smallest turbulent length scales must still be parameterized (Stull 1988). Only the computationally expensive direct numerical simulations (DNS) resolve the dissipative scales (at a resolution of millimeters to centimeters) within very small domains and, hence, do not require turbulence

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(or convection) parameterizations. Cloud microphysical processes, however, cannot be resolved in DNS.

For any physical process, there exists a range of model resolutions over which it is ambiguous whether or not that process should be parameterized. This resolution range is referred to as the NWP *gray zone*, which is scale specific to different phenomena. The gray zone for cumulus clouds (convective or cumulus schemes), for example, is reached at a coarser resolution than the gray zone for turbulence [planetary boundary layer (PBL) parameterizations]. Traditional parameterization schemes were designed to represent the subgrid-scale processes that are not explicitly resolved because they are spatially or temporally too small scale, too complex and expensive, or not well understood; but nonetheless affect the atmospheric state at the resolved scale. However, when decreasing the grid spacing below a certain value, previously unresolved scales become partially resolved and conventional closure assumptions break down (examples are given later in the introduction).

Following the general expectation that a higher resolution gives a better forecast (e.g., Roberts et al. 2009; Givati et al. 2012; Jang and Hong 2014), advances in computational capability have allowed operational models to enter the NWP convective gray zone. Although finer resolutions allow for a more accurate representation of surface fields and topography (Prein et al. 2015; Wagner et al. 2018), parameterization schemes are challenged by the gray zone problem and can diminish the forecast quality considerably. For example, Queen and Zhang (2008) and Sharma and Huang (2012) encountered such problems, finding that coarser resolution precipitation forecasts can actually perform better than those on 4- or 3-km grids. Within the convection-permitting scales, some studies (Kain et al. 2008; Schwartz et al. 2009; Chan et al. 2013; Johnson et al. 2013) show no added value or even worse precipitation forecast skill when refining the horizontal grid below 4 km. Other convection-permitting model experiments (Lean et al. 2008; Roberts and Lean 2008; Clark et al. 2012; Schwartz 2014; Smith et al. 2015), on the other hand, show that grids finer than 4 km can give a better representation of the observed convection, where explicitly resolved convection can improve land-atmosphere interactions and thus compare better to observational data than parameterized convection (Weisman et al. 1997; Marsham et al. 2013; Arnault et al. 2016; Klein et al. 2017; Mahoney 2016). These equivocal results are obtained when the convective parameterization is either turned on at scales it is not designed for, or it is abruptly turned off at a resolution of approximately 3–5 km. Therefore, the conventional parameterizations must be adjusted or redesigned to maintain their validity

in the gray zone and avoid the sharp change from fully parameterized to explicitly resolved convection (Arakawa et al. 2011; Hong and Dudhia 2012; Prein et al. 2015). Such new schemes are designed to be *scale aware* such that they can represent a smooth transition throughout all scales.

Conventional mass flux assumptions in cumulus parameterization schemes have the convective updrafts balanced by downdrafts within the same grid box, and require the updrafts to cover only a small fraction (less than about 10%) of the gridbox area (e.g., Arakawa and Schubert 1974; Tiedtke 1989; Kain and Fritsch 1990). However, updrafts can occur in different sizes from deep convective towers to turbulent eddies, so these assumptions generally only hold true for horizontal grid lengths larger than approximately 15–30 km (the largest updrafts extending the whole depth of the troposphere, causing both their vertical and horizontal scales to be of order 10 km) (Arakawa and Wu 2013). Although convection-permitting models do not require a parameterization for organized convection, and although grid lengths as large as 3 km may in some cases (depending on the dominant processes) already be sufficient to generally represent convective systems, they will not be able to represent the full spectrum of convective scales (Bryan et al. 2003; Wagner et al. 2018). To resolve the entrainment processes and turbulence within a cloud, a horizontal grid spacing finer than 100–250 m is generally required (Bryan and Morrison 2012). The gradually reduced cumulus activity in scale-aware schemes adjusts to this transition of scales and several studies (e.g., Mahoney 2016; Field et al. 2017; Hu et al. 2018) have shown superior performance in precipitation development when using such schemes. If no scale-aware scheme is employed, it is still best practice to turn off the cumulus scheme at a grid spacing smaller than from roughly 500 m to 5 km to help alleviate some of the gray zone issues when using traditional schemes (Wagner et al. 2018).

New deep convection cumulus schemes are either attempting a unified approach by rederiving equations (e.g., for the eddy flux) in such a way that the parameterization converges toward the explicit simulation (Kwon and Hong 2017; Arakawa and Wu 2013), or by using a conceptual or statistical approach to distribute entrainment, detrainment, and subsidence over the neighboring grid cells (Grell and Freitas 2014; Grell and Dévényi 2002). The key parameter for the convective scale awareness in mass-flux schemes is the fractional horizontal area of a grid cell that has convective updrafts. This fraction, which is usually assumed to be small (<10%), can be used as variable factor to reduce the eddy transport with decreasing grid spacing. Different formulations for this factor were

suggested. Grell–Freitas determines its value based on the effective radius of the updraft derived from the entrainment rate.

In terms of microphysics parameterizations, literature suggests that an expensive scheme is not needed for grid spacings coarser than about 10 km, while finer resolutions (starting with the convective gray zone) require enhanced complexity including the prediction of mixed phases (6-class schemes, including graupel) and number concentrations (double-moment schemes) (Bryan and Morrison 2012; Hong and Dudhia 2012; Han et al. 2019). At convection-permitting scales Adams-Selin et al. (2013) found that the graupel size representation in the microphysics scheme can matter more to the precipitation production than the number of moments (single- vs double-moment schemes). Furthermore including hail as a fourth ice variable in a microphysics scheme at 1-km grid spacing has shown some effect on light precipitation in a case study by Bae et al. (2019) and improvement of general in-cloud processes in a study by Tao et al. (2016).

Note that when individual cloud structures and complex topography become resolved at very fine resolutions, the description of other subgrid-scale processes must be reconsidered that are not within the scope of this study. For example, the horizontal component of the radiative transfer becomes relevant through shading clouds and orography.

PBL parameterizations account for the vertical mixing by atmospheric eddies of the dominant turbulent length scales from approximately 100 m to 3 km. At coarser horizontal resolutions one-dimensional PBL schemes are sufficient, assuming that all eddies are unresolved. At higher resolutions (e.g., LES) the vertical eddy mass fluxes become resolved and three-dimensional PBL schemes are required. According to Honnert (2016) the transition from parameterized to explicitly resolved turbulent mass fluxes in the PBL occur at grid lengths around 1 km.

Most parameterized effects (e.g., boundary layer processes, vertical mixing, convection, microphysics, and radiation) are closely linked (Coiffier 2011), and their formulations interact in a complex way (Prein et al. 2015). Therefore, they should be developed in a unified scale-aware framework [especially if considering a scale-growth development, i.e., from shallow convection to deep convection (Tomassini et al. 2017)]. However, intellectually and computationally this is a challenging task (Arakawa 2004), which is why the currently available parameterizations are often designed, tested and evaluated in a particular region and may be tuned to work best in a specific atmospheric environment. Therefore, when designing or verifying parameterizations, it is important to keep in mind that all scale interactions are

region, case, and variable specific and model performance may differ from one instance to another.

Overall model consistency—between the adiabatic gridscale processes (the “dynamics”) and all diabatic subgrid effects (the “physics”)—is essential when seeking a unified approach (Bauer et al. 2015; Gross et al. 2016; Field et al. 2017). A model system should be based on compatible fundamental and conceptual assumptions across all components (whether using a variable- or uniform-resolution mesh). The current trend in NWP model development is therefore striving to build “suites” of physics-dynamics packages that are robust but flexible enough to work for a large range of scales.

This new perspective that aims to bridge the gap between different scales and processes motivates continued evaluation of conventional versus scale-aware physics parameterizations. It is important to investigate under which circumstances, in which combination, and at which computational cost, schemes reveal their strengths and weaknesses. This study focuses on the NWP convective gray zone and aims to explore the gridscale-dependent model performance using different cumulus and microphysics schemes in the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) with the Advanced Research core (WRF-ARW). One real case study was selected for the investigation of each parameterization type (cumulus and microphysics). The experiments investigate how conventional parameterization schemes designed for coarser resolutions compare to new scale-aware schemes as we approach higher resolutions and enter the convective gray zone, where scale-aware schemes are expected to outperform traditional approaches. The different levels of complexity of the tested schemes also translate to different run times, and we discuss whether their performance justifies their computational expense. Hence, this study contributes to the body of knowledge on the benefits and usefulness of scale-aware cumulus schemes and sophisticated microphysics.

The model setup and methodology is presented in section 2, results and discussion are in section 3, while section 4 has the summary and conclusions.

2. Model setup and methodology

The WRF-ARW model (version 3.9.1.1) is used to simulate two case studies using different physics parameterizations and horizontal grid lengths initialized by the same dataset within each numerical experiment.

FIG. 1. The geographical location of the five nested WRF domains used in this study.

The initial and boundary conditions are provided every 3 h by the Global Forecast System (GFS) analysis data on a 0.5° latitude/longitude grid (roughly 50-km grid spacing). Five one-way-nested WRF Model domains ranging from 27 to 0.33 km (with a nesting ratios of three) are centered over the U.S. Southern Great Plains (Fig. 1), where a rich network of station observations from the Atmospheric Radiation Measurement (ARM) Climate Research Facility is available. Vertically, the WRF Model is configured with the model top at 50 hPa and 51 levels using a terrain-following, hydrostatic-pressure vertical coordinate. The cases chosen are: a mesoscale convective system to evaluate convective cumulus schemes, and a warm frontal zone with stratiform precipitation to evaluate microphysics schemes.

Each WRF run includes time-staggered spinup of 3 h for each domain, adding up to 15 h of total spinup

time that is not considered in the evaluation. To maintain numerical stability at all domains throughout each case, WRF was set to use an adaptive time step (Hutchinson 2007).

The convective and microphysics parameterizations were varied one at a time for all grids in each case study, while all other model settings and schemes were kept constant (Table 1). This way the nested domains are influenced by the performance of the same schemes on the coarser grids. The WRF Model configuration is summarized for both case studies in Table 1 and an overview of the used acronyms is given in Table 2. Two scale-aware cumulus schemes (Grell–Freitas and the multiscale Kain–Fritsch) were chosen for comparison with other conventional schemes, of which one is an adjustment type scheme (Betts and Miller 1986) while all other schemes are of the mass-flux type. Grell and Freitas (2014) implements the stochastic approach from Grell and Dévényi (2002) and adapts the scale awareness to the convective eddy transport equation as described in Arakawa et al. (2011), Arakawa and Wu (2013), and Wu and Arakawa (2014). The multiscale Kain–Fritsch scheme includes updates to the conventional Kain–Fritsch version concerning “subgrid-scale cloud–radiation interactions, a dynamic adjustment time scale, impacts of cloud updraft mass fluxes on grid-scale vertical velocity, and lifting condensation level–based entrainment methodology that includes scale dependency” (Zheng et al. 2016, p. 833). For details on the mathematical formulations and conceptual differences between the different parameterizations, the reader is referred to the original publications as cited in Table 2.

The results of all these model runs are investigated and evaluated against observational precipitation data in terms of local, spatial and temporal agreement. The bias and mean absolute error (MAE) are calculated from quality-controlled ARM station data, soundings, and from 4-km gridded analysis fields based on

TABLE 1. WRF Model configuration. The common settings column applies to both case studies.

Numerical experiment	Varied physics parameterizations	Common settings
Case study 1: Deep convective case 3–4 Jul 2017	Cumulus: KF, msKF, BMJ, Tiedtke, GF 1) on for all resolutions 2) off for $\Delta x \leq 3$ km Microphysics: WSM5	Dynamical core: ARW version 3.9.1.1 Horizontal grid dimensions: 27 km (91×91), 9 km (163×163), 3 km (262×262), 1 km (346×346), 0.33 km (424×424) Vertical layers: 51 (top at 50 hPa) Surface layer: MM5 Shortwave radiation: Dudhia Longwave radiation: RRTM PBL: YSU Land surface: Noah
Case study 2: Frontal precipitation case 15–16 Jan 2017	Cumulus: KF, GF Microphysics: WSM5, WDM5, Thompson, Morrison	

TABLE 2. Acronyms and references for the used parameterizations.

	Physics parameterization scheme	Acronym	Reference
Cumulus convection	Kain–Fritsch	KF	Kain (2004)
	Multiscale Kain–Fritsch	msKF	Zheng et al. (2016)
	Betts–Miller–Janjić	BMJ	Janjić (1994)
	Grell–Freitas	GF	Grell and Freitas (2014)
	Tiedtke	Tiedtke	Tiedtke (1989)
Microphysics	WRF single-moment 5-class scheme	WSM5	Hong et al. (2004)
	WRF double-moment 5-class scheme	WDM5	Lim and Hong (2010)
	1.5-moment 6-class Thompson	Thompson	Thompson et al. (2008)
	2-moment 6-class Morrison	Morrison	Morrison et al. (2009)
Planetary boundary layer (PBL)	Yonsei University scheme	YSU	Hong et al. (2006)
Surface layer	MM5 similarity scheme	MM5	Jiménez and Dudhia (2012)
Land surface	Unified Noah land surface model	Noah	Chen and Dudhia (2001)
Longwave radiation	Rapid Radiative Transfer Model	RRTM	Mlawer et al. (1997)
Shortwave radiation	Dudhia shortwave scheme	Dudhia	Dudhia (1989)

multisensor precipitation estimates (MPE, where applicable) (Lin 2011).

3. Results and discussion

a. Case study 1: Cumulus parameterization in the convective gray zone

In the afternoon (local time) on 3 July 2017, a mesoscale convective system (MCS) was initiated by a shortwave just behind a surface low pressure trough. As the MCS moved southeast across the Southern Great Plains, it intensified, forming a bowlike structure (Fig. 2) and reaching a spatial extent of approximately $300 \text{ km} \times 150 \text{ km}$. Embedded convective cells caused high local precipitation rates. The quality-controlled ARM ground stations available within the smallest WRF domain (0.33-km grid spacing) recorded

the highest rainfall rates of about 35 mm h^{-1} at a site in the 0000–0300 UTC period (not shown). The MPE analyzed local rainfall rates over 80 mm h^{-1} .

The five WRF Model configurations using different cumulus parameterization schemes (with parent-domain initialization at 0000 UTC 3 July 2017) yield significantly different results with respect to the organization of the convective system. Figure 3 compares the total precipitation ($>1 \text{ mm h}^{-1}$) between the cumulus schemes and grid lengths at the time of the observed highest precipitation rate (0200 UTC 4 July 2017). The corresponding observation from the MPE is seen in Fig. 4. The coarser-resolution runs (especially the 27-km grid) are insufficient to represent the convective development at the correct location or intensity. At a grid spacing of 3 km , the convective structure becomes resolved with individual embedded updrafts similar to those observed.

FIG. 2. Radar reflectivity observations (NEXLAB 2018) of the developing mesoscale convective system at different times (UTC) during 3–4 Jul 2017, framing the 1-km domain area.

FIG. 3. The hourly precipitation rate (mm h^{-1}) at 0200 UTC from WRF simulations (zoomed in to the 1-km domain area).

Simulations using a grid spacing of 3 km and finer seem to agree with each other better than the coarser 27- and 9-km results. Between the different cumulus schemes, Grell–Freitas and the multiscale Kain–Fritsch (Fig. 3, columns 3 and 4) match the MPE (Fig. 4) best for location, shape and intensity of the precipitation. The conventional Kain–Fritsch develops a weaker precipitation feature, which is delayed in time and therefore offset to the northwest of the location of the observed rainfall at the displayed time step. BMJ and Tiedtke trigger the convection at finer resolutions too early (hence a shift toward the southeast), and simulate a second minor precipitation area behind it.

Similar observations can be made from the time series of domain-averaged precipitation rates in Fig. 5 (where “0.33 km” represents the average of the entire 0.33-km domain, while all other grid-spacing trends average only the values of those coarser-resolution grid points that are inside the area covering the 0.33-km domain). While

Grell–Freitas’ high-resolution results (≤ 3 km) follow the averaged MPE analysis (black) curve best, the 27-km domain barely produces any precipitation. The 1- and 0.33-km domains of the Tiedtke scheme produce slightly lower rainfall rate averages, however, they do so 2–3 h too early. Tiedtke’s coarser resolution simulations miss the first convective shower and produce increasing rainfall after the actual event. A similar pattern is seen using the BMJ parameterization. The conventional Kain–Fritsch scheme yields the smallest averaged precipitation rates overall. Its better organized fine-resolution results give precipitation 1–2 h too late and too weak, while coarse-resolution domains show reduced precipitation intensity and earlier triggering. The multiscale Kain–Fritsch version exhibits significant improvement in precipitation intensity at high resolutions (≤ 1 km) compared to its conventional equivalent. However, its 3-km solutions overestimate the domain precipitation intensity, and the temporal offset

FIG. 4. The hourly analyzed precipitation rate (mm h^{-1}) at 0200 UTC from the gridded MPE (zoomed into the 1-km domain) using the same color scale as Fig. 3.

seen for Kain–Fritsch is still present for all grids using the multiscale version.

None of the conventional cumulus schemes (Kain–Fritsch, BMJ, and Tiedtke) were designed to be employed at grid sizes as small as our finest domains. Therefore, we also compare model runs that follow the best practice using conventional schemes. Namely, the cumulus scheme is turned off for grid spacings of 3 km and smaller, where we may expect to see these processes resolved. In these simulations, the 27- and 9-km solutions are identical since changes to the 0.33-, 1-, and 3-km domains have no feedback to the parent domains when using one way nesting. However, the differences seen at the finest grid spacings (with cumulus schemes turned off) result from the differences in input from their mother domains (here specifically, the 9-km domain), which are due to the general impact of the cumulus scheme on the coarser resolutions. Although the time shift is still present, the domain-averaged precipitation amounts are generally improved. The peak precipitation intensity (which is often too low with the cumulus schemes turned on) becomes slightly higher for all fine-resolution runs. The 3-km BMJ solution experiences significant improvement. Notably, the Grell–Freitas simulation, which already performed well, matches the MPE data (black curve) even better. This is because the Grell–Freitas scheme in WRF uses a maximum threshold of 0.9 for the convective coverage of a grid cell. This prevents the scheme from turning itself off entirely, which for this case seems to be the better practice at these grids. The only convection-permitting simulations for which hourly precipitation intensity is not improved is the multiscale Kain–Fritsch. In these runs the precipitation lasts longer, which results in higher accumulations and reduced forecast skill.

In NWP models, the total precipitation variable results from the combination of precipitation derived from microphysical processes at gridscale saturation (large-scale resolved precipitation as output from the microphysics parameterization) and precipitation from subgrid convective updrafts (as output from the cumulus parameterization). In a scale-aware framework with increasing resolution, one would expect to see a transition from the total precipitation being mainly produced by the convective parameterization for coarser grids, to increasingly being produced by the microphysics parameterization for finer grids.

To understand when and where the cumulus scheme is triggered, Fig. 6 displays the local contribution of microphysics versus cumulus scheme to the total precipitation [i.e., (subgrid – resolved scale)/total precipitation] corresponding to the precipitation field shown in Fig. 3. The general pattern is similar between all model runs: the center of the convective system yields precipitation mainly from the microphysics scheme (purple) due to gridcell saturation. This is embedded in an outer zone of subgrid-scale convective updrafts where precipitation is increasingly dominated by the cumulus scheme.

While the total precipitation from the Kain–Fritsch simulation is dominated by the convective component almost everywhere (green colors in column 1 of Fig. 6), the precipitation areas from Grell–Freitas and the multiscale Kain–Fritsch transition more smoothly from green to purple as the resolution increases. The BMJ scheme shows a similar development, with more cumulus scheme precipitation (green) than seen for the scale-aware schemes. Tiedtke’s total precipitation has the largest contribution from resolved-scale precipitation (purple) at coarse resolutions compared, and its convective precipitation areas (green) does not shrink at finer resolutions.

Figure 6 indicates the origin of the total precipitation within the horizontal domain, but only for one hour (0200 UTC). Averaged over the 0.33-km domain area and the time span of the case study (10 h from 2000 UTC 3 July 2017 to 0500 UTC 4 July 2017), Fig. 7 displays the fraction of convective precipitation as a function of resolution. The precipitation from the WRF runs using Grell–Freitas, Kain–Fritsch, and multiscale Kain–Fritsch comes exclusively from the cumulus scheme at the 27-km grid scale. As grid length decreases below 9 km, Kain–Fritsch’s total precipitation gradually includes more contributions from the microphysics scheme. The scale-aware schemes (especially Grell–Freitas), on the other hand, show a far more rapid change toward a resolved-scale-dominated precipitation at 3 km and below. BMJ shows a similar gridscale dependency to that of Kain–Fritsch, although it contains microphysics precipitation

FIG. 5. The 0.33-km domain-averaged precipitation from MPE observations (in black) and WRF Model simulations for different cumulus schemes (on or off) and grid lengths.

even at the coarsest resolutions. Tiedtke yields the opposite gridscale dependency in this case, with a higher convective precipitation contribution at finer resolutions. This, however, could be a result of the small sample size of grid points used to estimate the average value at coarse

resolutions (5×5 grid points of the 27-km grid over a 10-h evaluation period). None of the investigated cumulus schemes turn themselves off at any of the tested resolutions. The two scale-aware schemes reach the lowest value of averaged relative cumulus scheme

FIG. 6. The contribution of the total hourly precipitation rate from the cumulus scheme and the microphysics scheme at 0200 UTC from WRF simulations (corresponding to Fig. 3). Dark purple areas represent grid points where the total precipitation mainly results from the microphysics scheme; dark green areas represent grid points where the total precipitation mainly results from the cumulus scheme.

contribution with approximately 35%–25% (Grell–Freitas) or 50%–30% (multiscale Kain–Fritsch) at grid lengths between 3 and 0.33 km.

The 27-km domain yields generally low rainfall rates, which in most runs almost entirely originate from the cumulus scheme. At finer resolutions the microphysics schemes produce higher precipitation rates. Also at finer resolutions, the outer edge of the precipitation area is mostly represented by the convective cumulus scheme and is usually associated with smaller precipitation rates (not shown), while high total rainfall rates are strongly dominated by the microphysics scheme. Any precipitation areas containing contributions from the cumulus scheme in the Grell–Freitas simulations at $\Delta x \leq 3$ km yield low total precipitation rates ($< 5 \text{ mm h}^{-1}$). BMJ and Tiedtke allow higher total precipitation rates ($< 20 \text{ mm h}^{-1}$) with at least 50% contribution from the convective part even at higher resolutions (not shown).

The simulation with the conventional Kain–Fritsch, however, yields the highest total precipitation rates either entirely from the cumulus scheme ($\Delta x \geq 3$ km), or as a mix of cumulus and microphysics precipitation ($\Delta x \leq 1$ km).

A comparison of the vertical structure of atmospheric variables from sounding measurements with interpolated model results (not shown) was possible only for one location and time during the convective development (Lamont at 0000 UTC 4 July 2017). Most model runs were too warm (especially at coarse resolutions), too dry, and too windy (especially at high resolutions). These biases are also present in the boundary layer, which is important for convective development. Grell–Freitas yields the smallest bias for atmospheric moisture at this time and location, especially in the boundary layer. At the time of the sounding observation, the different WRF simulations were not at the same state of

FIG. 7. The time and domain-averaged fraction of the convective over the total precipitation as function of grid length.

the convective system; more samples at different locations and times would be necessary to draw conclusions on systematic errors.

In summary, all convective cumulus schemes show poor agreement with observations at coarser resolutions (27–9 km). For finer resolutions, Grell–Freitas shows the best agreement with observations. Since Grell–Freitas reduces its convective precipitation component significantly at fine resolutions, it appears logical that other runs using schemes that do not reduce their convective component automatically (because they are not scale aware) perform better when turned off manually. The conventional convective (mass-flux) parameterization formulations balance updrafts with subsidence within the same grid cell. This can suppress the full convective development at fine resolutions, when updrafts cover a considerable portion of the gridcell area and the downdrafts of the convective movement should instead be redistributed over neighboring grid points. Turning conventional schemes off at the critical resolution (here 3 km) can help to minimize this problem. However, the gray zone problem suggests that the necessary transition cannot be represented by a single grid length.

The superior performance of the Grell–Freitas scheme comes at the cost of a longer run time. In this application the Intel-compiled WRF code was run on an HPC cluster using Open MPI and no hyperthreading on two Intel Xeon CPU E5–2683 v4 (2.10GHz) compute nodes, which each has 32 cores. The WRF run of 36 model forecast hours (including 15 h of staggered spinup) on a total of 64 cores, with the Grell–Freitas scheme turned on throughout all resolutions, took 13 h and 19 min of run time (using 2 full compute nodes) and was the longest of all executed runs (see yellow bars in Fig. 8).

FIG. 8. Comparison of the WRF total and relative computation times (per run or per time step) to finish all domain grids using different cumulus parameterizations.

The multiscale Kain–Fritsch simulation, which also performed well, had a run time one hour faster than Grell–Freitas. The fastest (but perhaps least accurate) simulation used the Kain–Fritsch parameterization for all domains and took 11 h and 3 min of run time (17% faster than Grell–Freitas) for a 36 h forecast. Note also that all simulations called the cumulus scheme at every time step, and used the adaptive time step. The latter means that run times are not only a result of the computational requirements of the parameterization, but also of the simulated atmospheric conditions. Therefore Grell–Freitas, which shows the strongest convective development with higher horizontal wind speeds and vertical updrafts (not shown here), requires a smaller time step to avoid numerical instability, resulting in a longer total run time than the Kain–Fritsch simulation. Kain–Fritsch was able to maintain its numerical stability with a larger time step because it simulates a much weaker convective system. Dividing the total run time by the number of time steps and domains gives an average value for computational time required to calculate one time step (note that domains with finer grid spacing require shorter, hence more time steps). This method allows a relative comparison and indicates that Grell–Freitas requires about 3% more computational time than Kain–Fritsch per numerical time step (see green bars in Fig. 8).

b. Case study 2: Microphysics parameterization in the convective gray zone

Four microphysics parameterization schemes of different complexity using single or double moments and 5 or 6 classes of hydrometeors were tested for 15–16 January 2017. The coarsest domain is initialized at 0900 UTC 3 January 2017, in order to evaluate model data starting

FIG. 9. Radar reflectivity observations (NEXLAB 2018) of the developing frontal precipitation at different times (UTC) during 16 Jan 2017, framing the 1-km domain area.

from 0000 UTC 4 January 2017, allowing 15 h for spinup. This case investigates an area of stratiform precipitation with embedded convection associated with an inverted trough extending northward from a surface low. The band of light to moderate precipitation moved across the high-resolution WRF domains from 0000 to 1000 UTC (Fig. 9).

In the previous case study very different results were found for the Kain–Fritsch and the Grell–Freitas cumulus schemes, so both convective parameterizations are tested with each microphysics scheme to investigate their impact on the different microphysics schemes for this study.

Figure 10 shows the total hourly precipitation rate using Grell–Freitas at a time when the front just passed the finest domain, for each of the microphysics schemes. The model solutions can be compared to the analysis field (MPE) in Fig. 11. It becomes evident that the choice of the microphysical parameterization makes little difference to the precipitation field, whereas the grid spacing and the cumulus scheme (not shown) have a larger impact. The modeled precipitation fields look more and more fissured with increasing resolution using both Kain–Fritsch (not shown) and Grell–Freitas for the convective parameterization.

The smoothness of the observed precipitation is best represented by the simulations for the 9- and 3-km grid. The 27-km domain washes out the details seen in the observed fields, while the finer-resolution domains produce a rough structure with jagged edges and embedded cells of much higher rainfall rates than observed.

Since all schemes in Fig. 10 are similar, it is difficult to distinguish the best performing microphysics scheme by visual comparison with the analysis in Fig. 11. The area-averaged hourly precipitation rates (not shown) indicate that Grell–Freitas’s precipitation varies considerably with grid spacing and microphysics scheme, whereas

Kain–Fritsch simulations have very similar spatially averaged precipitation across all grid spacings and microphysics schemes.

This can also be seen in the Figs. 12a and 12b, which compare the MAE of the hourly precipitation calculated at each grid point inside the 0.33-km domain area at every hour between 0000 and 1200 UTC 16 January 2017. This verification approach, however, overly penalizes model simulations that may produce the precipitation feature in the right intensity and organization, but with a spatial or temporal shift [the so-called *double penalty effect* (Rossa et al. 2008)]. To eliminate the spatial component in the MAE, Figs. 12c and 12d represent the MAE calculated from the area-averaged hourly precipitation rates. To eliminate the temporal component, Figs. 12e and 12f show the MAE values calculated from the 12-h accumulated precipitation at each grid point inside the 0.33-km domain to determine the error of the total precipitation in a spatially limited area throughout the time period of the case study. Note that the MAE values of accumulated precipitation intrinsically have a larger magnitude than hourly precipitation (cf. the ordinate scale).

The Kain–Fritsch simulation errors have no significant grid-length dependence, whereas the scale-aware Grell–Freitas errors do (Fig. 12). The Grell–Freitas runs have a slightly worse MAE than Kain–Fritsch at 27 km, but are generally better at all finer-resolution domains. The exception is when precipitation is first accumulated over time (Figs. 12e and 12f). This suggests that Grell–Freitas errors result more from location than timing of precipitation features for this case. This spatial error increases with decreasing grid length by more than 100% for some schemes (Fig. 12f). Two exceptions to the similar performance of all microphysics schemes are as follows: 1) the WSM5 scheme has a particularly large spatial error using Grell–Freitas, and 2) the Morrison

FIG. 10. Comparison of the hourly precipitation rates (mm h^{-1}) at 0400 UTC from WRF simulations using four different microphysics schemes (zoomed in to the 1-km domain area), while using Grell–Freitas as the cumulus scheme for all four simulations.

scheme exhibits noticeably larger errors when using the Kain–Fritsch at finer resolutions.

Overall, the Thompson microphysics parameterization seems to perform slightly better than the other schemes at finer resolutions when using Kain–Fritsch for the cumulus parameterization (Figs. 12a and 12c). The Thompson scheme also gives comparatively small spatial errors for the accumulated precipitation using Grell–Freitas (Fig. 12f). However, the spatially averaged rainfall rates using Grell–Freitas (Fig. 12d) show a higher temporal error for Thompson. In the fine-resolution Grell–Freitas domains, the Morrison scheme performs best compared to all other microphysics schemes. For the fine-resolution Kain–Fritsch domains, however,

Morrison performs worse than the other microphysics scheme.

The fraction of the precipitation from the convective parameterization scheme is much smaller for this case study than in the previous case since the precipitation is more stratiform in this case. The Kain–Fritsch cumulus scheme produces 25%–40% of the total precipitation at the coarsest resolution (not shown). This fraction decreases with increasing resolution. When using Grell–Freitas, the cumulus scheme is barely triggered in this case and contributes very little or no convective precipitation to the total rainfall.

The histograms of the frequency of all precipitation rates occurring throughout the event from the MPE

FIG. 11. The hourly analyzed precipitation rate (mm h^{-1}) at 0400 UTC from the gridded MPE (zoomed into the 1-km domain area) using the same scale as Fig. 10.

analysis field (not shown) indicates rainfall rates of up to 15 mm h^{-1} . However, light rainfall rates below 1 mm h^{-1} occur most frequently. Many WRF simulations overestimate the precipitation intensity (especially the double-moment schemes and the fine-resolution 1- and 0.33-km domains) and generate rainfall rates of up to 38 mm h^{-1} (not shown). Using the Grell–Freitas cumulus scheme, the histograms from the WSM5 and Morrison microphysics schemes are most consistent with the observed rates throughout all tested grid lengths. With the Kain–Fritsch cumulus scheme, only the WSM5 scheme produces reasonable precipitation intensity at all resolutions.

Only 6-class microphysics schemes are able to represent graupel. Hence, both (single- and double-moment) WSM5 and WDM5 schemes are missing this species. The time- and space-averaged mixing ratios of the hydrometeors in the vertical column (not shown) shows that the Morrison scheme simulates more graupel than Thompson, and the graupel content increases with higher resolutions. The Thompson microphysics scheme produces the largest snow mixing ratios at all grid lengths and for both cumulus schemes. However, it rarely indicates any cloud ice, which all other schemes produce at the top of the cloud. While the cloud ice average from the WSM5 schemes reaches down to a pressure level of about 700 hPa, the Morrison scheme restricts it to higher altitudes (above approximately 400 hPa). The WSM5 and WDM5 schemes produce generally very similar vertical structures.

The most time-consuming simulations were the configurations using the Grell–Freitas cumulus scheme with either Thompson or Morrison for the microphysics scheme (Fig. 13). Both runs, simulating 27 forecast hours (including 15 h of time-staggered spinup time), took 10 h and 5 min to run. Interestingly, the quickest

run was also using Grell–Freitas, although this time combined with the single-moment WSM5 microphysics scheme. This run would save 46% of the run time versus the more advanced microphysics schemes.

Considering the large differences in run time depending on the choice of microphysics parameterization together with the small difference in forecast performance seen in this case study, this suggests that more sophisticated schemes are not always worth their computational expense. The costly Thompson and Morrison schemes showed different errors behavior depending on the applied cumulus scheme. The simpler WSM5 and WDM5 microphysics schemes did not stand out, but neither did they disappoint in their performance. Considering the significant run-time savings, these schemes could offer sufficient accuracy in a time-sensitive (e.g., operational) framework. However, more case study analyses are necessary to discover the dependency and interaction between convection and microphysics parameterizations. Additionally, no definite correlation between the performance of the microphysics schemes and grid spacing was found.

4. Summary and conclusions

The NWP gray zone was investigated for two different case studies using the WRF-ARW model run at various grid spacings with different cumulus and microphysics parameterization schemes.

First, the performance of five different cumulus schemes was analyzed throughout convective gray zone resolutions for a mesoscale convective system case study that caused intense precipitation in the Southern Great Plains. Considerable differences between the spatial distribution, the accumulated amount, and the local intensity of the simulated precipitation area were seen between the different schemes.

The scale-aware schemes (especially Grell–Freitas) produced the smallest errors, outperforming other conventional cumulus schemes in timing and intensity of the precipitation. This appeared to result from their smooth transition from subgrid (cumulus) to resolved-scale (microphysics) precipitation. However, the best-performing Grell–Freitas scheme was also the most time-consuming scheme (17% slower than the fastest simulation, which used Kain–Fritsch).

Also the multiscale Kain–Fritsch showed considerable improvement at high resolutions compared to the conventional Kain–Fritsch scheme. This agrees with findings by Mahoney (2016) and Hu et al. (2018). However, in their studies the superior performance of the multiscale Kain–Fritsch scheme was due to the reduction of excessive rainfall as compared to the conventional Kain–Fritsch.

FIG. 12. MAE of the precipitation rate between 0000 and 1200 UTC 16 Jan 2017. (left) MAEs for WRF runs using Kain–Fritsch for the convective parameterization. (right) MAEs for WRF runs using Grell–Freitas. Smaller values represent smaller errors.

In the present study, however, the multiscale Kain–Fritsch simulation enhanced the underrepresented precipitation seen with the conventional Kain–Fritsch scheme.

Forecast error converged toward a minimum at approximately 3-km horizontal grid spacing for almost all cumulus schemes (except the multiscale Kain–Fritsch). Especially for schemes that were not scale aware, MAEs slightly increased again at finer resolutions.

The performance of the finer grids, even for those using the Grell–Freitas scheme, can be enhanced by switching the cumulus scheme off for 3 km and below. This agrees with [Wagner et al. \(2018\)](#), who concluded from a 1-yr study over Germany, that (independent of topography) a 5-km grid does not require a cumulus parameterization where Grell–Freitas is rather inactive anyway. Using a scale-aware version of the simplified Arakawa–Schubert

FIG. 13. Comparison of the WRF total and relative computation times (per run or per time step) to finish all domain grids using different microphysics and cumulus parameterizations.

scheme, [Kwon and Hong \(2017\)](#) also found that the cumulus scheme can affect the organization of precipitation bands at a fine resolution even though the scheme's activity is reduced. They recommend turning the scale-aware cumulus scheme off at 1-km grid spacing, where convection is mostly resolved. [Han and Hong \(2018\)](#) agree with these findings for heavy precipitation events, whereas light precipitation was often suppressed at 3-km grid spacing without the scale-aware simplified Arakawa–Schubert scheme. In the present experiments only the multiscale Kain–Fritsch scheme performed best when turned on for all grids.

However, the overall superior performance of Grell–Freitas seen in this case study contradicts findings from [Sikder and Hossain \(2016\)](#), which identified BMJ as the best performing cumulus scheme in combination with different microphysics schemes (especially WSM5) on 27- and 9-km grids for monsoonal precipitation. In their study Grell–Freitas exhibited poor results during rainy periods with lighter accumulations at finer grid spacings. [Lim et al. \(2014\)](#) also found Grell–Freitas to be the worst performing cumulus scheme over the Korean Peninsula for a summer monsoon season, when compared to the Kain–Fritsch, BMJ, and Arakawa–Schubert ([Pan and Wu 1995](#)) schemes. Their study, however, investigates a range of grid lengths down to 12 km only. [Ngailo et al. \(2018\)](#) also found Kain–Fritsch to be the best performing cumulus scheme for extreme precipitation in Tanzania, where Grell–Freitas produced very high MAEs. Encouraging results with Grell–Freitas were found by ([Fowler et al. 2016](#)) on a variable-resolution mesh centered over South Africa. Note that these studies were conducted in a different convective environment and climate than the present study. In contrast, over the American continent, [Hu et al. \(2018\)](#) found that the cumulus options Grell–Freitas, Tiedtke, and the multiscale Kain–Fritsch perform well compared to other schemes (including the conventional

Kain–Fritsch or BMJ schemes) at a grid spacing of 20 km. [Gao et al. \(2017\)](#) also found the Grell–Freitas scheme to show superior performance in a 36–12–4-km WRF setup when compared with the conventional Kain–Fritsch scheme, which tended to trigger convection too early and overpredict precipitation in the summer season. Although the conventional Kain–Fritsch simulation in the present study underpredicts the convective case, it is of interest that Grell–Freitas was evaluated to be the best performing scheme. Notably, the U.S. studies were performed over a heavily instrumented region, which suggests that the details concerning the spatial distribution and intensity of precipitation in the analysis grids may be more reliable and robust.

Whereas the choice of the cumulus parameterization led to substantial differences in convective development in WRF, in the second case study of stratiform precipitation, different microphysics schemes produced similarly skillful precipitation forecasts. This agrees with the findings from other studies (e.g., [Huang et al. 2015](#); [Sikder and Hossain 2016](#); [Zeyaeyan et al. 2017](#); [Hu et al. 2018](#)). Although the differences between different microphysics options are small and the results are based on a single case study only, we found that lowest MAEs were associated with the Kain–Fritsch cumulus scheme in combination with the Thompson microphysics scheme at fine resolutions. The lowest MAEs with the Grell–Freitas scheme are found at fine resolutions when it is combined with the Morrison scheme. However, when Grell–Freitas is chosen, the cumulus scheme is rarely triggered, so the vast majority of precipitation is produced by the microphysics scheme. Precipitation errors associated with Grell–Freitas runs had a greater dependence on grid spacing because the microphysics scheme is more active in producing precipitation [as also found by [Bernardet et al. \(2017\)](#) and [Biswas et al. \(2018\)](#)]. The WSM5 scheme performed similarly to the Thompson and Morrison schemes, while being simpler and up to 31% faster. [Sikder and Hossain \(2016\)](#) found that more complex microphysics schemes perform better for high rainfall events and finer grids where cumulus schemes are typically turned off. In this study, however, different microphysics options were only tested for a case of stratiform precipitation with fairly light rain rates.

The robustness of our results is limited because this study considered only two cases, which is not enough to make a conclusive statement about the performance of the individual schemes. Rather, this study adds to greater the body of knowledge on the performance of cumulus and microphysics schemes across the convective gray zone. The microphysics option by itself did not make a considerable difference for the stratiform precipitation event. For convective cases where the microphysics scheme produces

most of the heavy precipitation in the center of the system, scheme choice may have more of an impact. More work is needed to investigate these interconnections.

Simulations with grid spacings of 3 or 1 km exhibited the best performance on average—however, caution is advised when verifying fine resolution results below convection-permitting scales (1–4 km). Enhanced small-scale detail and noise can contribute to errors (Lorenz 1969) and therefore decrease the precipitation forecast skill due to double penalty even though the representation of convection may look more realistic (Done et al. 2004; Roberts and Lean 2008; Clark et al. 2009). Note, furthermore, that the nested high-resolution runs are affected by the imperfection of their input from the coarser domains, which use the same convective schemes, respectively.

The experiments in this study were designed to investigate the impact of varying a single parameterization type, while keeping all other settings in the WRF Model constant. Best practices suggest a few other adjustments when entering such high resolutions where the gray zone problem becomes an issue also for turbulent eddies. For example, one could consider adjusting the diffusion or eddy coefficient as well as using a scale-aware boundary layer scheme (e.g., Shin and Hong 2015), which could further enhance the performance of the fine-resolution domains.

The scale-aware approach of the Grell–Freitas scheme was superior to all conventional convective parameterizations, at least in part because it transitioned the portion of convective versus resolved-scale precipitation depending on the grid length. Although, the multiscale Kain–Fritsch could not outperform Grell–Freitas, the superiority of a scale-aware formulation is borne out when comparing both versions of Kain–Fritsch. Other conventional mass-flux schemes could follow the example set by Arakawa et al. (2011) and Grell and Freitas (2014), and consider a revision toward a scale-aware formulation.

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