Reviewer1

Overall assessment

This manuscript implements an observation-constrained generalized double-moment scaling normalization (GDMN) representation of the raindrop size distribution (DSD) within the WDM6 bulk microphysics scheme and evaluates its impact using a convection-permitting real-case simulation over the Korean Peninsula.

The study is technically sound, clearly structured, and addresses an important limitation of conventional bulk microphysics schemes, specifically the use of fixed DSD shape parameters. The integration of an observation-derived normalized DSD function h(x), based on Boseong 2DVD measurements (2018–2019), into an operational modeling framework represents a meaningful and non-trivial contribution. The results demonstrate consistent improvements in convective cell propagation and in the vertical reflectivity structure (CFAD), indicating that the modified DSD representation affects both microphysical processes and storm-scale dynamics.

The contribution is best understood as a practical, model-embedded implementation and evaluation of GDMN within an operationally relevant framework (WDM6), rather than a conceptual introduction of scaling normalization.

With several targeted clarifications, primarily concerning the novelty statement and the robustness of the observation-derived DSD representation, the manuscript is suitable for publication in *Geoscientific Model Development* after minor revision.

Szyrmer, W., Laroche, S., and Zawadzki, I.: A microphysical bulk formulation based on scaling normalization of the particle size distribution. Part I: Description, J. Atmos. Sci., 62, 4206–4221, 2005.

: We sincerely appreciate the reviewer's valuable comments and suggestions. The manuscript has been revised accordingly based on the reviewer's feedback. Detailed responses are provided under each review point.

Primary comments

1. Refinement of the "first" claim (Abstract)

The current "first" claim should be refined to better reflect the actual scope of the contribution. As written, it may be interpreted as implying conceptual novelty of scaling-normalization approaches in bulk microphysics. However, the principal novelty of this study lies in the observation-constrained implementation of GDMN within WRF WDM6 and its evaluation in a convection-permitting real-case simulation.This can be addressed without weakening the manuscript by restricting the scope of the claim and briefly acknowledging related prior work. The following wording is recommended: "To our knowledge, this study presents the first implementation of an observation-constrained GDMN-based rain DSD representation within WRF WDM6 and evaluates its impacts in a convection-permitting real-case simulation; related scaling-normalization bulk formulations exist (e.g., Szyrmer et al., 2005)." This revision maintains the manuscript's originality while ensuring consistency with the existing literature.

: As suggested by a reviewer, we have revised the corresponding sentence from "This study is the first to adopt the Generalized Double-Moment scaling Normalization (GDMN) method to represent the rain Drop Size Distribution (DSD) in a bulk-type cloud microphysics scheme, specifically the Weather Research and Forecasting (WRF) Double-moment 6-class (WDM6) scheme. " to "To our knowledge, this study presents the first implementation of an observation-constrained GDMN-based rain DSD representation within WRF WDM6 and evaluates its impacts in a convection-permitting real-case simulation; related scaling-normalization bulk formulations exist." in the Abstract

2. Stability of the observation-derived normalized DSD function h(x)

The central modification in this study relies on the observation-derived normalized DSD function h(x) and its associated parameters (c, μ). Therefore, it would be beneficial to provide additional evidence for the stability of this representation. I encourage the authors to quantify the robustness of h(x), for example through a simple cross-validation between the 2018 and 2019 datasets, or by referring to relevant supporting studies. This addition would substantially improve confidence that the observation-derived DSD representation is sufficiently stable for the intended modeling application.

: We thank the reviewer for this valuable comment. We included the following sentences in the revised manuscript. "Previous research by Bang et al. (2020) demonstrated that the normalized DSD function $h(x)$, derived from observations over South Korea (2011-2015) and Oklahoma (1998-2006), USA, exhibits no substantial differences despite the distinct geographical characteristics of the two regions. These findings support the robustness of the observation-derived $h(x)$representation and suggest that it is sufficiently stable for the intended modeling application in this study."

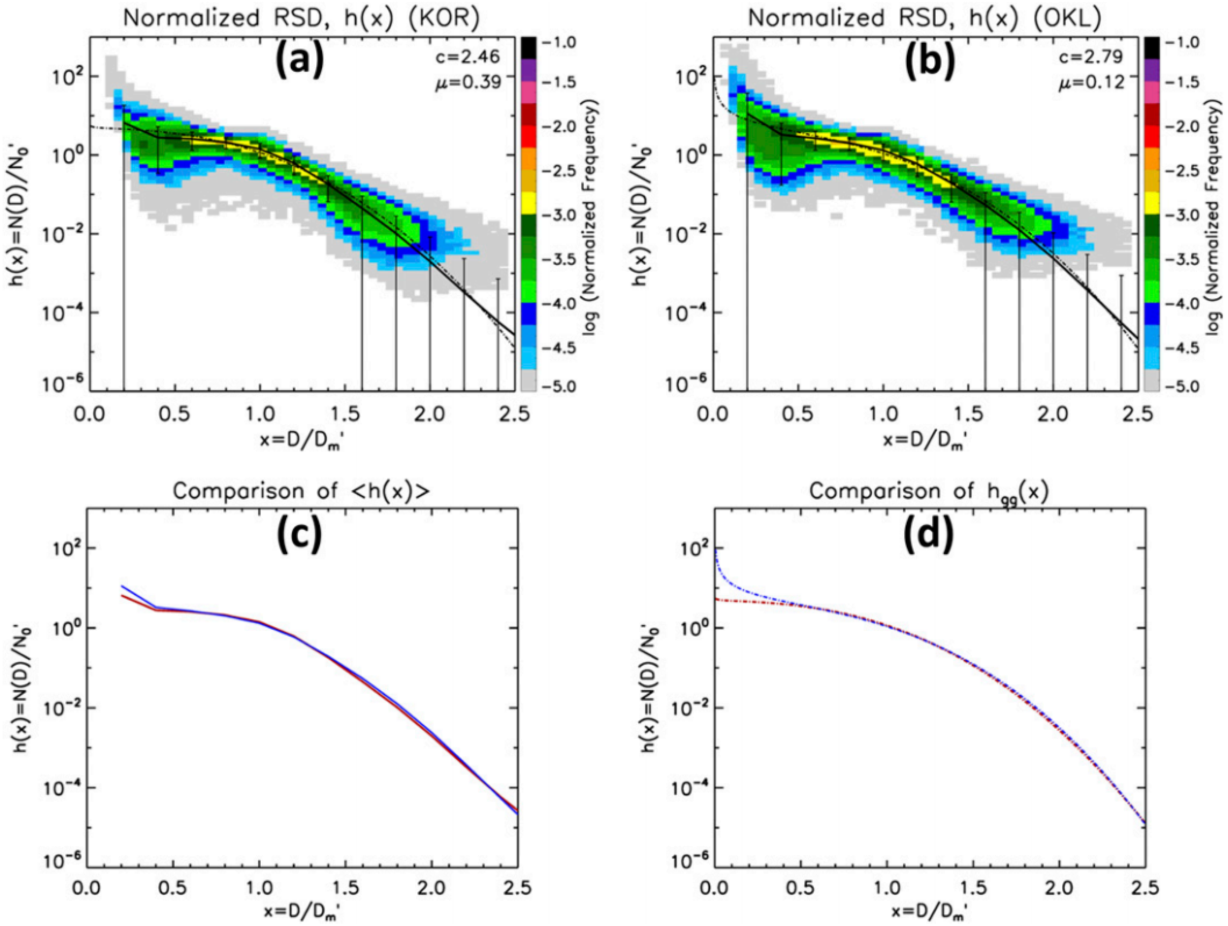

Fig. R1. Comparison of normalized DSD for South Korea (KOR) and Oklahoma (OKL). (a) h(x)–x graph for KOR. (b) h(x)–x graph for OKL. The solid line is the average h(x) and the dot–dash line is least squares fit. The vertical bar is the standard deviation. (c) Average h(x) and (d) fitted h(x). Red (blue) is KOR (OKL).

The Figure R1 shows the normalized DSDs of rain for South Korea and Oklahoma. The normalized DSDs collapse into a similar single curve, particularly in the mid-size range (0.5–1.5). The average and fitted h(x) functions are nearly identical between the two regions despite differences in region and environment. These results suggest that the normalized DSD shape is relatively robust across regions.

3. Robustness of model results to parameter uncertainty

The conclusions of the manuscript depend on how the modified DSD representation affects microphysical processes, particularly rain evaporation and its impact on near-surface cooling and convective propagation. It is therefore important to demonstrate that the reported improvements are not sensitive to a specific parameter choice.

To further support the robustness of the proposed mechanism, the authors may consider a limited set of sensitivity experiments in which (c, μ) are perturbed within a plausible observational range. It would then be useful to show how the principal outcomes respond, particularly in terms of accumulated precipitation distribution, statistical skill scores, and CFAD-based diagnostics. If the main conclusions remain qualitatively consistent across these perturbations, this would strengthen the physical interpretation and reduce concerns regarding parameter sensitivity. In this context, it is worth noting that previous studies have shown that gamma DSD parameters may exhibit variability and interdependence depending on fitting approaches and observational uncertainty (e.g., McFarquhar et al., 2015), which further motivates demonstrating robustness with respect to parameter choice. In addition, it is noted that slightly different values of (c, μ) arise during the derivation of the normalized DSD (e.g., $c = 2.70$, $\mu = 0.24$ in intermediate steps and $c = 2.60$, $\mu = 0.29$ in the final formulation). A brief clarification of whether similar simulation outcomes are obtained when using alternative parameter values would further support the consistency and robustness of the proposed approach.

: We thank the reviewer for this valuable and insightful comment. To address the reviewer's concern, we conducted an additional sensitivity experiment (GDMN_SEN) using the observed values of c and μ derived from disdrometer measurements collected over Boseong during 2018–2019 and Incheon during 2020–2023, resulting in $c = 2.65$ and $\mu = 0.49$. These results indicate that the c and μ parameters do not vary significantly when applying the generalized DSD formulation.

As shown in Figure R2-R4 and Table R1, the simulation results obtained using different parameter values ($c = 2.65, \mu = 0.49$) exhibit behavior consistent with those using the original parameter values ($c = 2.60, \mu = 0.29$) in terms of accumulated precipitation, CFAD, convection evolution, and statistical scores. Based on these sensitivity experiment results, we have added the following statement to the revised manuscript: "The differences in microphysical processes, particularly rain evaporation and near-surface cooling between WDM6 and GDMN, are not sensitive to the prescribed c and

μ parameters, as these parameters do not vary substantially within the generalized DSD function."

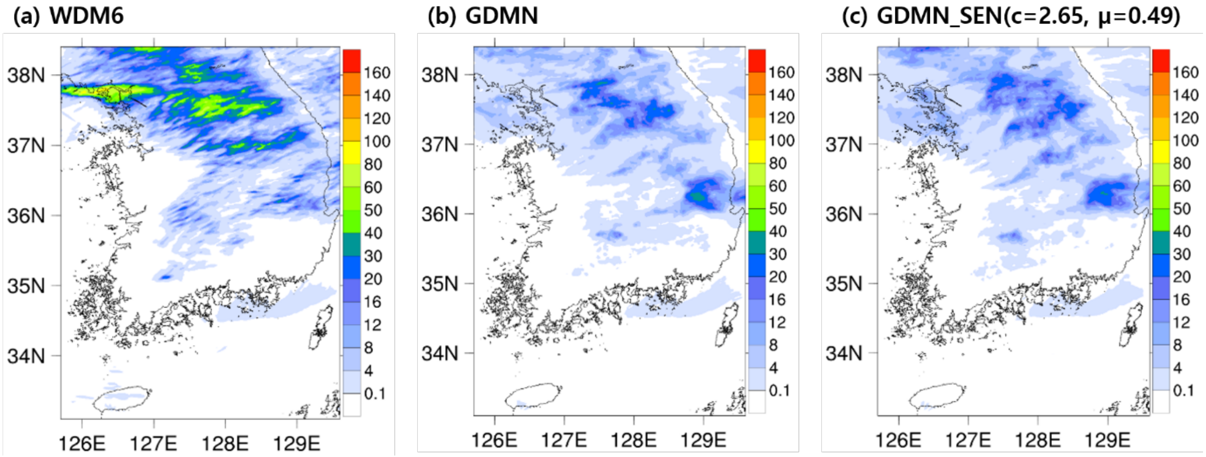
(a) WDM6 (b) GDMN (c) GDMN_SEN(c=2.65, μ=0.49)

Fig. R2. Accumulated surface precipitation (mm) during the analysis period (from 02:00 to 17:00 UTC on 6 August 2013) for (a) WDM6, (b) GDMN, and (c) GDMN_SEN.

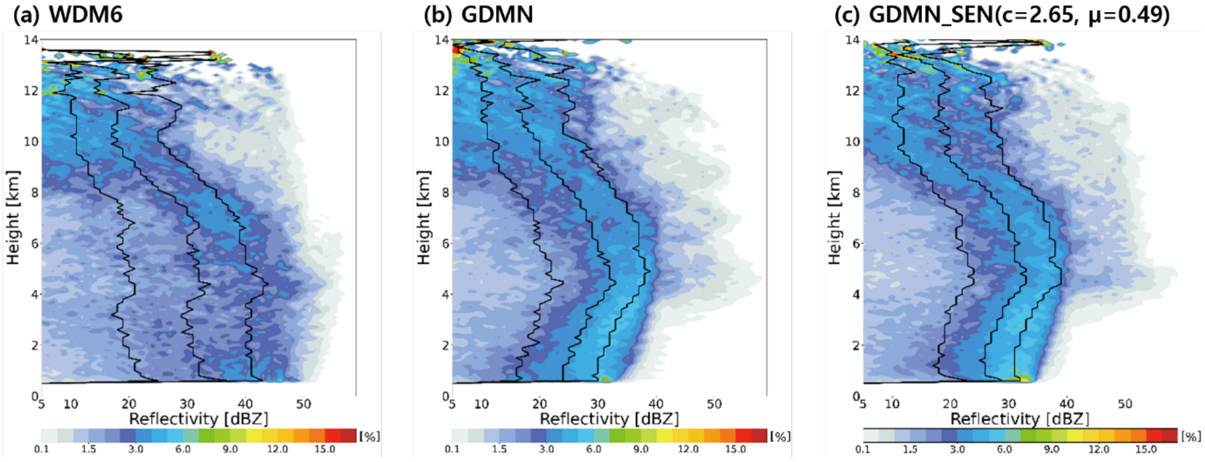
(a) WDM6 (b) GDMN (c) GDMN_SEN(c=2.65, μ=0.49)

Fig. R3. Contoured Frequency by Altitude Diagram percentiles at the KWK radar sites for (a) WDM6, (b) GDMN, and (c) GDMN_SEN during the analysis period.

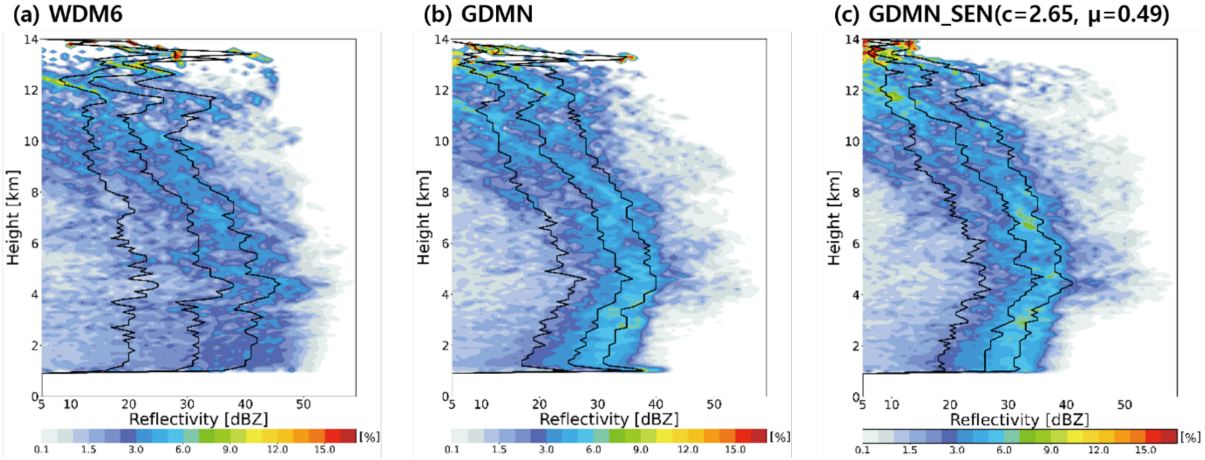
(a) WDM6 (b) GDMN (c) GDMN_SEN(c=2.65, μ=0.49)

Fig. R4. Contoured Frequency by Altitude Diagram percentiles at the GDK radar sites for (a) WDM6, (b) GDMN, and (c) GDMN_SEN during the analysis period.

Table R1. Same as Table 2 in the original manuscript but with the GDMN_SEN.

	RMSE	BIAS	POD	FAR	ETS
WDM6	6.72	2.0	0.16	0.70	0.05
GDMN	5.03	1.39	0.18	0.68	0.07
GDMN_SEN	5.20	1.21	0.17	0.68	0.06

4. Additional quantitative support for propagation improvement

The manuscript argues that WDM6-GDMN improves convective cell movement and propagation. While the qualitative analysis is convincing, this conclusion would benefit from limited quantitative support. It is recommended to include at least one object-based metric (e.g., centroid displacement or cell tracking) and one neighborhood-based verification metric, such as the Fractions Skill Score (FSS). These additions would provide a clearer and more robust assessment of spatial forecast skill.

: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have added the Fractions Skill Score (FSS) to Table 2, which shows values of 0.14 for GDMN and 0.13 for WDM6. We also added the following sentence: “The calculated Fractions Skill Score (FSS) also indicates that GDMN outperforms WDM6.”

5. Clarification of the physical mechanism (cold-pool perspective)

The manuscript attributes improved propagation to enhanced near-surface cooling associated with increased rain evaporation (e.g., Figs. 9–12). This interpretation is physically plausible and well supported qualitatively. However, the causal linkage would be strengthened by including a simple cold-pool diagnostic, such as near-surface temperature (or virtual potential temperature) deficit and a qualitative estimate of propagation speed. Such diagnostics can be derived from existing model output and would help directly connect microphysical changes to dynamical responses.

: We thank the reviewer for this insightful comment. Figures 10a and 10b clearly show enhanced near-surface cooling in GDMN. To address the reviewer’s concern more explicitly, we additionally conducted a sensitivity experiment, LH_TEST, which is identical to the GDMN experiment except that the latent cooling, associated with rain evaporation, was removed.

Figure R5 presents the vertical cross-section of temperature differences between the experiments (GDMN − LH_TEST) along the red line shown in Fig. 2b. The temperature differences between the two experiments indicate that evaporative cooling substantially contributes to the enhanced near-surface cold pool in GDMN. These results provide additional support for our proposed mechanism that increased rain evaporation strengthens low-level cooling, which in turn contributes to improved convective cell movement and propagation.

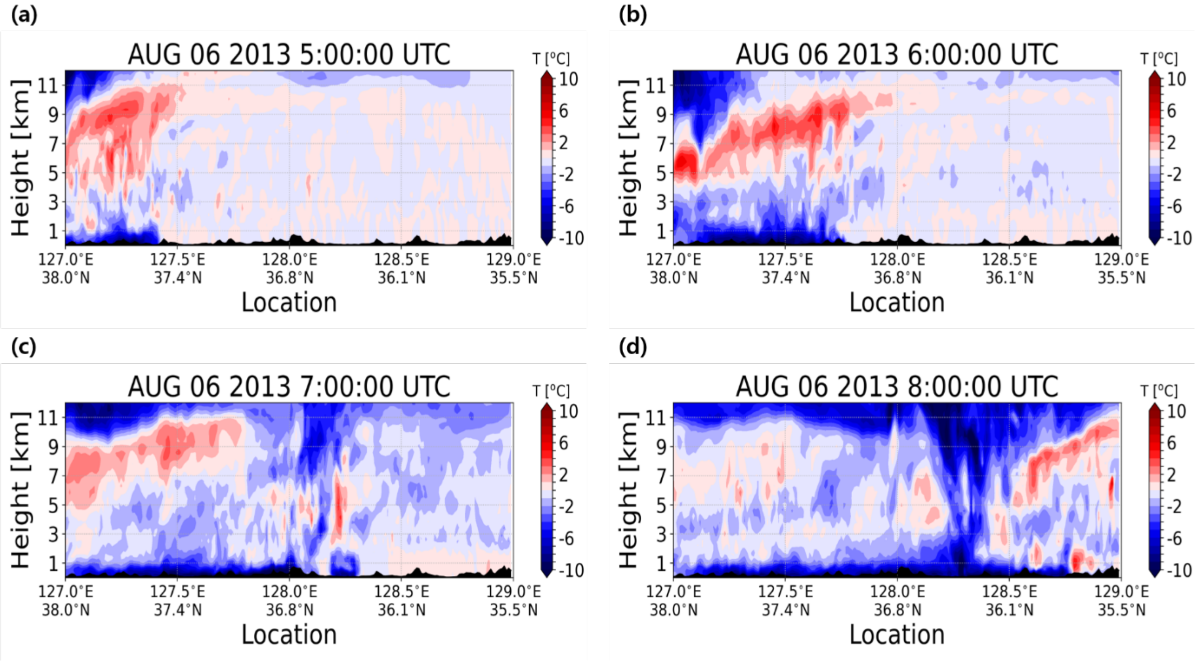

Fig. R5. Differences (GDMN – LH_TEST) in temperature (°c), shown with terrain (black color) along the cross-section indicated by the red line in Fig. 2b at 6 August 2013. (a) 05UTC, (b) 06UTC, (c) 07 UTC and (d) 08UTC.

Minor Comments

1. Line 394: “Numerial” -> “Numerical” Line 394: “Numerial” -> “Numerical”

: Revised accordingly.

2. Line 396: “alleviates limitation” -> “alleviates limitations”

: Revised accordingly.

3. Line 405: “overestimate reflectivity” -> “overestimates reflectivity”

: Revised accordingly.

4. Line 409: “us more realistically” -> “is more realistically

: Revised accordingly.