December 4, 2025

Dear Reviewer:

We are submitting our revised manuscript, entitled "**Characterizing orographic clouds and precipitation in Qilian Mountains, northwestern China**" to *Natural Hazards And Earth System Sciences*.

We thank the reviewer for the detailed and helpful comments to improve the manuscript. Responses to the individual comments are provided below. Reviewer comments are in **bold**. Author responses are in blue plain text. Modifications to the manuscript (Tracked changes) are highlighted in red. Line numbers in the responses correspond to those in the final submitted version.

The submitted manuscript has been revised based on reviewers' comments.

Sincerely,

Lingbin Kong,
Professor
School of Computer and Artificial Intelligence/School of Geoscience and Technology, Zhengzhou University
Zhengzhou, China

General comments:

Ren et al., in this manuscript, present, a detailed investigation of a stratocumulus precipitation event over the Qilian Mountains (northwestern China) on 16–17 August 2020, focusing on the dynamic role of local circulation and the resulting microphysical transformations. The study is highly relevant to understanding water resources and weather modification efforts in arid and semi-arid regions. The authors employ a robust, high-resolution WRF model setup (down to 333 m grid spacing) combined with valuable observational data, including in-situ aircraft measurements (LWC, CIP, PIP), weather radar (CINRAD/CD), and station precipitation data.

The paper's primary strength lies in its detailed analysis of the diurnal variation of the mountain-valley wind circulation and its forcing mechanism on precipitation. The finding that strong valley wind circulation, exhibiting obvious diurnal characteristics, persists even under general cloud and rainfall conditions due to the complex and high terrain, is a significant contribution.

Furthermore, the quantitative microphysical analysis clearly demonstrates a transition from warm cloud process dominance (characterized by high graupel content and warm rain/graupel melting accounting for 53.9% of rainwater source in the afternoon) to cold cloud process dominance (characterized by snow melting accounting for 92.6% of rainwater source in the evening/early morning). The model is generally shown to accurately simulate the stratocumulus precipitation system and the changes in radar echo with elevation. This work provides important insights into the physical processes governing precipitation in this complex topographical region.

However, some central points related to dynamic forcing mechanisms remain ambiguously stated, and certain model-observation discrepancies warrant further discussion or sensitivity testing before publication.

We thank the reviewer for the insightful comments. We have made improvements to the basic formatting of the manuscript, including font size and notation on equations.The response to each comment is listed below.

1. Under Section 3.2, the authors note a significant discrepancy in precipitation simulation: the simulated rainfall and rain belt range were larger than measured, with the simulated heavy precipitation center averaging 38.83 mm compared to the measured average of 25.32 mm. The authors attribute this to possible model error, complex terrain influence, or the selected physical scheme. A more detailed investigation or discussion on the sensitivity to the chosen physics (specifically the Thompson microphysics scheme) would strengthen the validation section, especially given the crucial role of microphysics in the subsequent analysis.

Thanks for the comment. We agree that a deeper exploration strengthens the validation section. We sincerely thank the reviewer for this constructive feedback regarding the discrepancy between the simulated and observed precipitation amounts, and for highlighting the importance of a more in-depth discussion on the sensitivity to the chosen microphysics scheme. In section 3.2 of our manuscript , we indeed note that the simulated 24-hour cumulative precipitation was generally higher than the observations, with the simulated heavy precipitation center averaging 38.83 mm compared to the observed 25.32 mm. We initially attributed this to potential model errors, the influence of the region's complex terrain, and the chosen physical parameterization scheme.

As suggested by the reviewer, we agree that a more detailed discussion of the sensitivity to the microphysics scheme, particularly the Thompson scheme used throughout this study, would strengthen the validation. We have previously conducted systematic research on parameterization scheme selection for the Qilian Mountains region. In our earlier published study (Zhang et al., 2022, Arid Zone Research, Vol. 39, No. 6, pp. 1717-1727; provided as supporting material), we explicitly evaluated four microphysics schemes (Thompson, Morrison2-mom, WSM3, and WDM6) for simulating a stratiform cloud precipitation event in the Qilian Mountains using the WRF model. The results, evaluated by TS, BIA, TSS, and ETS scores, indicated that the Thompson scheme performed the best overall for this region, effectively capturing the location of the rainband and the center of heavy precipitation, albeit with a systematic overestimation of precipitation amount.The scores for the 24-hour accumulated precipitation are summarized in Table 3 and Figure 1.

Building on that foundational work, we selected the Thompson scheme for the high-resolution simulations in the present study. The overestimation observed here is consistent with the trend identified in our prior research. We believe this overestimation in the Thompson scheme may be related to its specific treatment of mixed-phase processes and the conversion rates among hydrometeors (e.g., ice to snow, snow/graupel to rain), which can be more active compared to other schemes, potentially enhancing precipitation production under the strong forced uplift conditions of the Qilian Mountains terrain.

In the revised manuscript, we have expanded the discussion in Section 3.2 to explicitly address this point.

Table 3. Verification scores for 24-hour accumulated precipitation simulated by different microphysics schemes (Zhang et al., 2022).

Scheme	TS	BIA	TSS	ETS
Thompson	0.98	1.02	0.20	0.05
Morrison2-mom	0.98	1.02	0.10	0.00
WSM3	0.90	0.96	-0.08	-0.02
WDM6	0.94	1.00	-0.01	-0.008

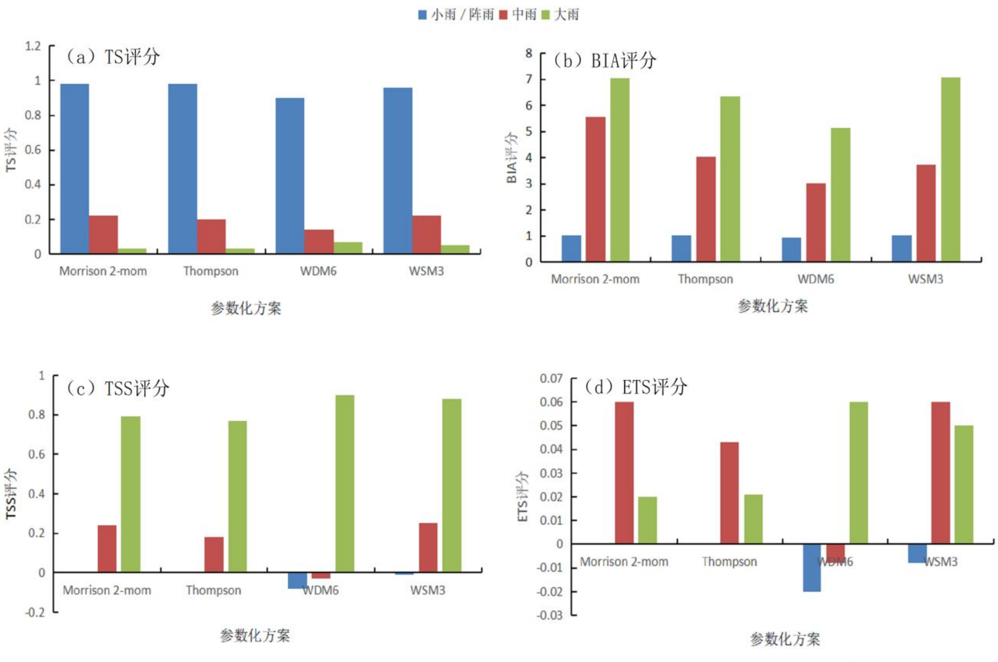

Fig.1 Four cloud microphysics schemes simulate the TS, BIA, TSS and ETS scores of different levels of 24h precipitation(Zhang et al., 2023).

2. The aircraft microphysical data used for comparison was collected between 08:50 and 12:00 on August 16, with the specific vertical detection analyzed between 09:32 and 09:56. This time frame occurs before the peak heating/convective stage (13:00) analyzed dynamically. The authors classify the afternoon stage (convective, warm rain dominant) starting at 12:00. It would be beneficial to explicitly place the morning aircraft observations within the context of the diurnal cycle (e.g., as part of the transition phase or early stratiform phase) rather than contrasting them only with the general characteristics of the entire event.

Thanks for the comment. We acknowledge that explicitly situating the morning aircraft data within the diurnal cycle context would enhance the clarity and coherence of our analysis. In the current manuscript, the aircraft measurements (08:50–12:00 BT, with detailed vertical profiling from 09:32–09:56 BT) were primarily used for a point-in-time validation of the model's ability to represent cloud liquid water and ice crystal number concentrations (Section 3.2). We agree that contrasting these findings primarily with the "overall event characteristics" or the later-defined "afternoon convective stage" (peaking around 13:00 BT) may create a temporal disconnect. Based on the synoptic and thermodynamic evolution presented (Figures 2-4, 10-13), the period of the aircraft flight can indeed be characterized as a transitional or development phase within the diurnal cycle.

In the revised manuscript, we have refined our narrative to explicitly integrate the aircraft observations into the diurnal framework. In Section 3.2, when introducing the aircraft data, we explicitly stated that these observations captured the late morning transition phase, as the system evolved from the early morning stratiform-influenced conditions toward the peak afternoon convection. In Section 3.3, we clarified and adjusted the stage definitions to include this "Development/Transition Phase" preceding the "Afternoon Convective Phase," and noted that the aircraft validation targeted this specific period. In the Discussion (Section 4) and Conclusions, we contextualized the microphysical findings from the aircraft (e.g., ice crystal habits, presence of supercooled water) as representative of the microphysical state during the development of the orographic clouds, which provided the initial conditions for the subsequent intense ice-phase and mixed-phase processes that became dominant later in the diurnal cycle.

3. The simulated ice crystal number concentration (reaching 600 L) was generally higher than the observed CIP particle number concentration (highest near 40 L at 5.6 km and 5.9 km). Given that the cold cloud process is determined to be dominant during much of the precipitation cycle, this large overestimation of ice particle number concentration in the model needs reconciliation or a dedicated sensitivity test of the ice nucleation parameterization.

We sincerely thank the reviewer for raising this important point regarding the discrepancy between the simulated and observed ice crystal number concentrations, and for suggesting a valuable direction for future investigation. We acknowledge that the simulated ice crystal number concentration is notably higher than the observed CIP (Cloud Imaging Probe) particle number concentration in the 5.6–6.9 km layer. We appreciate the reviewer's connection of this overestimation to the dominant cold-cloud processes identified in our study. We agree that understanding this discrepancy is crucial for the credibility of the microphysical analysis. While a full, dedicated sensitivity test of the ice nucleation parameterization within the Thompson scheme is beyond the immediate scope of this particular case study analysis, we offer the following explanations and context based on known challenges in model physics and our specific setup.

The CIP probe primarily images particles in the 25–1550 μm size range. It is possible that a significant population of very small ice crystals or irregular ice habits that are less efficiently detected/imaged by the CIP contribute to the model's ice crystal number concentration. The model's ni variable represents a bulk number concentration for all ice-phase particles categorized as cloud ice, which likely includes these small and nascent ice crystals that are challenging to measure in situ. This known issue of comparing bulk model variables to instrument-specific observations has been noted in previous intercomparison studies.

Ice Nucleation Parameterization in the Thompson Scheme: The Thompson microphysics scheme, which our prior research (Zhang et al., 2022) identified as optimal for the Qilian Mountains region, uses a temperature-dependent empirical formulation for ice nucleation. Under the strongly forced orographic uplift and the presence of abundant supercooled water , such schemes can generate high concentrations of ice crystals, particularly in the deposition/condensation-freezing regime. This may be a contributing factor to the elevated simulated ni. The reviewer's suggestion for a sensitivity test on ice nucleation is excellent and aligns with our planned future work to further refine model performance for this region.

Context from Our Prior Validation: While this specific case shows a quantitative overestimation in ice number concentration, our overall validation in Section 3.2

indicates that the model successfully captured the vertical structure and the relative enhancement of ice crystal concentration within the cloud layer (e.g., the peak near 5.9 km). Furthermore, the model reproduced the key observed microphysical processes (dominance of cold-cloud processes, ice growth via deposition and aggregation, and rain formation primarily from melting ice-phase particles) as detailed in the manuscript. This suggests that while the absolute concentration may be biased, the simulated microphysical pathways and evolution are qualitatively robust.

We will address this point directly in the revised manuscript:In Section 3.2, where the comparison is presented, we will add a brief discussion acknowledging the quantitative discrepancy in ice crystal number concentration. We will note the potential reasons, including (a) the representativeness of the CIP measurement for the full ice crystal population defined in the model, and (b) the known tendency of the employed microphysics scheme to produce higher ice concentrations under strong, sustained uplift conditions.We will incorporate a sentence in the Discussion (Section 4) or Limitations subsection, stating that the overestimation of ice crystal number concentration highlights a known challenge in cloud microphysics parameterization, particularly for orographic clouds. We will explicitly cite the reviewer's suggestion and state that future work will include sensitivity experiments focusing on ice nucleation parameterizations to improve the quantitative accuracy of ice crystal forecasts in regional models for the Qilian Mountains.

In the revised manuscript, we directly addressed the points raised above. In Section 3.2, where the comparison is presented, we added a brief discussion acknowledging the quantitative discrepancy in ice crystal number concentration. We noted potential reasons, including (a) the representativeness of the CIP measurement relative to the full ice crystal population as defined in the model, and (b) the known tendency of the employed microphysics scheme to generate higher ice concentrations under strong, sustained uplift conditions. Furthermore, in the Discussion (Section 4), we included a statement clarifying that this overestimation reflects a recognized challenge in cloud microphysics parameterization, especially for orographic clouds. We also explicitly acknowledged the reviewer’s suggestion and indicated that future work will involve sensitivity experiments focusing on ice nucleation parameterizations to improve the quantitative accuracy of ice crystal forecasting in regional models over the Qilian Mountains.

Thank you again for this constructive and technically insightful comment.

Specific comments:

（1）For organization and smooth flow, always define or expand abbreviations where they are first used (e.g., Ln 121: CINRAD/CD; Ln 130: CMORPH).

Thanks for the comment. We have made modifications in the manuscript.

（2）In all Table and Figure numberings, leave a colon (:) after the number.

Thanks for the comment. We have made modifications in the manuscript.

（3）leave a space between values and SI units attached (e.g., Ln 161: 700hPa, Ln 230: 40L-1 etc.)

Thanks for the comment. We have made modifications in the manuscript.

（4）Always use the past tense form when talking about past studies. Change “is”

to "was" in a few places like Lns 191, 197, etc.

Thanks for the comment. We have made modifications in the manuscript.

（5）It would be best to ensure units for model vs observation comparisons (e.g., stick to either g/kg or g m-3 for water content comparisons).

Thanks for the comment. We have made modifications in the manuscript.

（6）Remove parentheses in text references of Figure numbers with letters. For instance, Figure 9 (a) should be Figure 9a when referenced in the Figure discussion. Also, consider referencing specific subpanels in Figures when discussing them for easy comprehension.

Thanks for the comment. We have made modifications in the manuscript.

（7）Some Figure captions can be better written to make them intuitive at first glance (E.g., Figure 10, 15 and 16).

Thanks for the comment. We have made modifications in the manuscript.

（8）Ln 20: delete "and".

Thanks for the comment. We have made modifications in the manuscript.

（9）Ln 26: delete "the downslope wind produces".

Thanks for the comment. We have made modifications in the manuscript.

（10）Ln 30-31: This should read as "In the evening and early morning, weak convective and stratiform clouds are dominant."

Thanks for the comment. We have made modifications in the manuscript.

（11）Ln 33: reword "change trend".

Thanks for the comment. We have made modifications in the manuscript.

（12）Ln 42: … China. This is also the ….

Thanks for the comment. We have made modifications in the manuscript.

（13）Ln 44. Here and elsewhere, delete the space before the period.

Thanks for the comment. We have made modifications in the manuscript.

（14）Ln 50: delete "heat".

Thanks for the comment. We have made modifications in the manuscript.

（15）Ln 53: airflow.

Thanks for the comment. We have made modifications in the manuscript.

（16）Ln 64 – 66: This statement needs to be referenced.

Thanks for the comment. We have made modifications in the manuscript.

（17）Ln 66: Weather Research and Forecasting (WRF).

Thanks for the comment. We have made modifications in the manuscript.

（18）Ln 70: "showed".

Thanks for the comment. We have made modifications in the manuscript.

（19）Ln 71: Here and elsewhere, change "WRF mode" to WRF model

Thanks for the comment. We have made modifications in the manuscript.

（20）Ln 74: insert "of" after distributions.

Thanks for the comment. We have made modifications in the manuscript.

（21）Ln 89: Here and elsewhere in the document, leave a space before "(".

Thanks for the comment. We have made modifications in the manuscript.

（22）Ln 107-108: Should read as: "This paper investigates the typical topographic cloud precipitation process over the Qilian Mountains using

observational data …"

Thanks for the comment. We have made modifications in the manuscript.

（23）Ln 144: insert "this study" before discuss….

Thanks for the comment. We have made modifications in the manuscript.

（24）Ln 116: add "s" to reveal.

Thanks for the comment. We have made modifications in the manuscript.

（25）Ln 122: Place coordinates after Station.

Thanks for the comment. We have made modifications in the manuscript.

（26）Ln 125: delete "and".

Thanks for the comment. We have made modifications in the manuscript.

（27）134: Change "The Object of the measurement" to "Parameters Measured".

Thanks for the comment. We have made modifications in the manuscript.

（28）Ln 140: Add "respectively" after Figure 1.

Thanks for the comment. We have made modifications in the manuscript.

（29）In Table 2, change "Mode top height" to "Model top height".

Thanks for the comment. We have made modifications in the manuscript.

（30）Ln 145: Use lower case for D03 and D04.

Thanks for the comment. We have made modifications in the manuscript.

（31）Ln 149: changed "appeared" to "showed up".

Thanks for the comment. We have made modifications in the manuscript.

（32）Ln 153: change Figure 2 and Figure 3 to "Figures 2 and 3".

Thanks for the comment. We have made modifications in the manuscript.

（33）Ln 168: correct unit °C.

Thanks for the comment. We have made modifications in the manuscript.

（34）Ln 181: Verify that "18:00" is correct or supposed to be "19:00".

Thanks for the comment. We have made modifications in the manuscript.

（35）Ln 183: I disagree with CTT being lower than -40 °C. This is where it is useful to maintain the box showing the study area in Figure 4. I think you actually meant higher than -40 °C (as in warmer). Actually, the blue box mentioned in the caption is missing from the plots.

Thanks for the comment. We have made modifications in the manuscript.

（36）Ln 194: … and in a large range. It is…

Thanks for the comment. We have made modifications in the manuscript.

（37）Ln 200: Add "(2022)" to Zhang al.

Thanks for the comment. We have made modifications in the manuscript.

（38）Ln 202: What is this being compared with?

Thanks for the comment. We have made modifications in the manuscript.

（39）Ln 218: Change Figure 8 to Figure 7.

Thanks for the comment. We have made modifications in the manuscript.

（40）Ln 230: delete "the".

Thanks for the comment. We have made modifications in the manuscript.

（41）In Figure 6, your height axis is not consistent with the corresponding unit.

Thanks for the comment. We have made modifications in the manuscript.

（42）Ln 298 – 302: Split these into 2 sentences.

Thanks for the comment. We have made modifications in the manuscript.

（43）Ln 307: What does “large extent Condition” mean?

Thanks for the comment. We have made modifications in the manuscript.

（44）Ln 334: Change Figure 12a to Figure 11a.

Thanks for the comment. We have made modifications in the manuscript.

（45）Ln 350: Delete “which is”.

Thanks for the comment. We have made modifications in the manuscript.

（46）Ln 351: Change “caused by” to “as a result of”.

Thanks for the comment. We have made modifications in the manuscript.

（47）Ln 367: Change “wind field and terrain height of 10 m on the ground” to “surface winds (10 m – winds and terrain height)”.

Thanks for the comment. We have made modifications in the manuscript.

（48）Ln 380 – 383: To avoid redundancy, I suggest using something like: “Similar analysis is done at 02:00 on 17 August (Figure 13). During this time, ...”

Thanks for the comment. We have made modifications in the manuscript.

（49）In Figure 11, (b) and (c) are really quite hard to interpret, especially the reflectivity contours (supposed to be black solid lines). I recommend using color fill for reflectivity, solid and dashed lines for negative & positive temperature values respectively. Perturbation wind vectors can stay the same. Also, the AB line is not visible enough.

Thanks for the comment. We have made modifications in the manuscript.

（50）Ln 425: Change “topographical” to “orographic”.

Thanks for the comment. We have made modifications in the manuscript.

（51）Ln 428: leave a space after “clouds”.

Thanks for the comment. We have made modifications in the manuscript.

（52）In Figure 14, Panel or subplot labels are out of order.

Thanks for the comment. We have made modifications in the manuscript.

（53）Ln 497: Remove space after the closed bracket.

Thanks for the comment. We have made modifications in the manuscript.