Response to reviewer's comment on "*Aerosols-precipitation elevation dependence over the Central Himalayas using cloud-resolving WRF-Chem numerical modeling*" by Adhikari and Mejia.

We are very thankful to all the reviewers for their kind and insightful comments. We believe these comments improved the quality of the manuscript. Here, we have presented the reviewer's comment in black and our responses in blue.

Reviewer #1:

The study presents convection permitting simulations on how aerosol affects the amount of precipitation in the mountainous terrain. Although the results are very similar to earlier studies in similar environments, it nicely adds on existing literature and in the discussion references are adequately made. As the aerosol effect on precipitation is highly relevant especially in the locations vulnerable for climate change and changing aerosol emissions, the study fits well in the scope of ACP. I find the manuscript well written and have only a few comments I suggest being addressed before acceptance to the final publication.

As both ARI and ACI effects are analyzed, a more detailed information related to ACI would be needed. Currently there is no information about CCN or cloud droplet number concentrations and how those are affected by changing emissions. As the manuscript itself contains already quite many figures, these could be also provided as supplementary material, but discussed in the main text together with changes in updraft velocities and liquid/ice water content.

We thank Reviewer #1 for the valuable comments/feedback and the positive appreciation of the manuscript. These comments helped us to improve the manuscript.

As suggested, we have added the supplementary figure (S3) of vertically integrated cloud droplet number concentration and discussed it in the text as follows:

"Figure S3 shows a clear difference in the vertically integrated cloud droplet number concentration between the simulations, with an increasing order from the CLEAN (lowest), CTL, and D_AERO (highest) simulations, in a similar order of aerosol concentration. Similarly, more aerosols are activated as cloud droplets over the lower elevational belt (<2000 m ASL) compared to relatively cleaner higher mountainous regions (> 2000 m ASL)."

The increase in the cloud droplet number concentration is maximum for the D_AERO (doubling the aerosols simulation scenario) with the highest aerosol concentration. The result is within the expectation that the more the aerosol concentration, the more the activation of cloud droplets, further increasing the confidence in the model output, and it did not change the overall conclusion of the result.

Minor comments

Lines 84-90: Barnan and Gokhale (2022) is later referenced, but as the aerosol effect is studied also there with quite similar setup as here, the clear difference between that and this study should be presented. The same holds also to Adhikari and Mejia (2022).

Thank you for the feedback. The comparison with the Barman and Gokhale (2022) and Adhikari and Mejia (2022) are made in the results and discussion section (Line 424-431). As suggested by the reviewer, we also added the following text to the introduction (Line 78-81):

"Barman and Gokhale (2022), using a coarse (10 km) resolution WRF-Chem simulation, showed aerosol could modulate the precipitation over the mountainous terrain of north-eastern India during the spring season. Also, a case study by Adhikari and Mejia (2022) showed Central Himalayan early monsoon precipitation enhanced due to the remotely transported dust aerosols."

Line 190: Are the aerosol properties only altered in WRF-Chem simulation always employing the same boundary conditions from CAM-Chem? If so, is the domain large enough to exclude the aerosol effect caused by aerosol changes outside the boundaries of WRF-domain?

We are not employing the same boundary conditions from CAM-Chem during the simulation. As mentioned in the text (Line 161-163), lateral boundary condition information for chemistry is provided from the CAM-Chem at a six-hourly temporal resolution. Also, aerosols loading from BCs are changed consistently in the CTL and CLEAN simulation.

Line 194: Aerosol radiation “feedback” should probably be “interaction”.

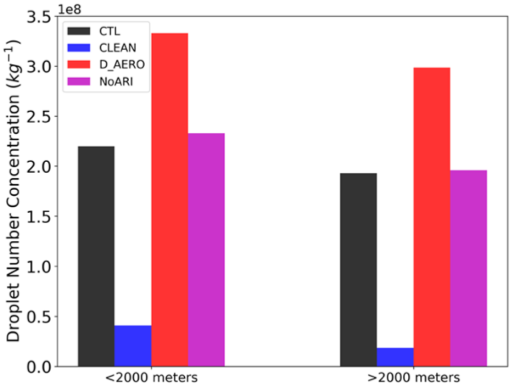
Thank you for pointing it out. We have edited the text as suggested.

3.1 Model Evaluation: It is well known that the relationship between AOD and CCN concentration might ne very week. Still there is no discussion how well the simulated aerosol size distribution matches with observations. Are such observations completely missing from the area?

It would have been great to have an observational network of aerosol size distribution data to evaluate the simulated output in our study area. For example, the observational campaign such as Regional Aerosol Warming Experiment and the Ganges Valley Aerosol Experiment (RAWEX-GVAX) conducted at the Nainital, India (west of CenHim region defined in our paper) during 2011-12 could have provided the observational evidence of the physical, optical, and chemical properties of aerosols (Gogoi et al., 2015; Dumka et al., 2021). Furthermore, these types of field campaigns will also provide insights into the aerosol distribution (size and types) over the Central Himalayan region, which will help improve confidence in the aerosol and CCN representation in the model and eventually help reduce the biases and uncertainties. This study motivates future studies conducting field campaigns in such a complex topography as the Central Himalayas.

We added Fig. S3 (also below), showing the vertically integrated cloud droplet number concentration for different simulation runs. The simulation with the higher aerosol loading (D_AERO that is doubling aerosols) has the maximum activated cloud droplet, partly addressing the data limitations and uncertainties in the aerosol loadings.

“Figure S3 shows a clear difference in the vertically integrated cloud droplet number concentration between the simulations, with an increasing order from the CLEAN (lowest), CTL, and D_AERO (highest) simulations, in a similar order of aerosol concentration. Similarly, more aerosols are activated as cloud droplets over the lower elevational belt (<2000 m ASL) compared to relatively cleaner higher mountainous regions (> 2000 m ASL).”



“Figure S3 *Mean of vertically integrated cloud droplet number concentration averaged over the CenHim region for the terrain elevation below and above 2000 m ASL.”*

Lines 297-299: It is difficult to see the elevational gradient in observed precipitation both using direct observations in Fig 5 or satellite data in Fig 6. Thus, stating that model captures the elevational gradient based on data presented is quite strongly said and seems actually opposite that model simulations has a gradient nonexistent in the observations.

We performed the precipitation analysis for the individual 90 stations (not shown in the paper but shown below), which shows similar precipitation distribution (lower over lowlands of Central Nepal, maximum at the mountainous region, and reduced over northwestern Nepal) as simulated at those particular stations. However, as discussed in the text, some biases might exist due to most of the rain gauge stations being located on the valley floor. In the paper, we show the mean total cumulative precipitation for stations located at different elevational ranges. We agree with the reviewer that the model does not agree with the satellite-based observational data in terms of elevational gradient and might be due to the scale differences and uncertainties associated with the satellite product over the complex terrain, as we have discussed in lines 308 to 315. Also, as shown in Figs. 5e-h, the satellite product underestimates the precipitation compared to both model and the station data. For better clarification, we edited the text as follows:

"In general, though some biases in precipitation exist, the model showed the overall feature of the precipitation distribution with lower rainfall over the lowlands, maximum mountainous precipitation associated with orographic forcing, and reduced leeward precipitation over northwestern Nepal and the TP."

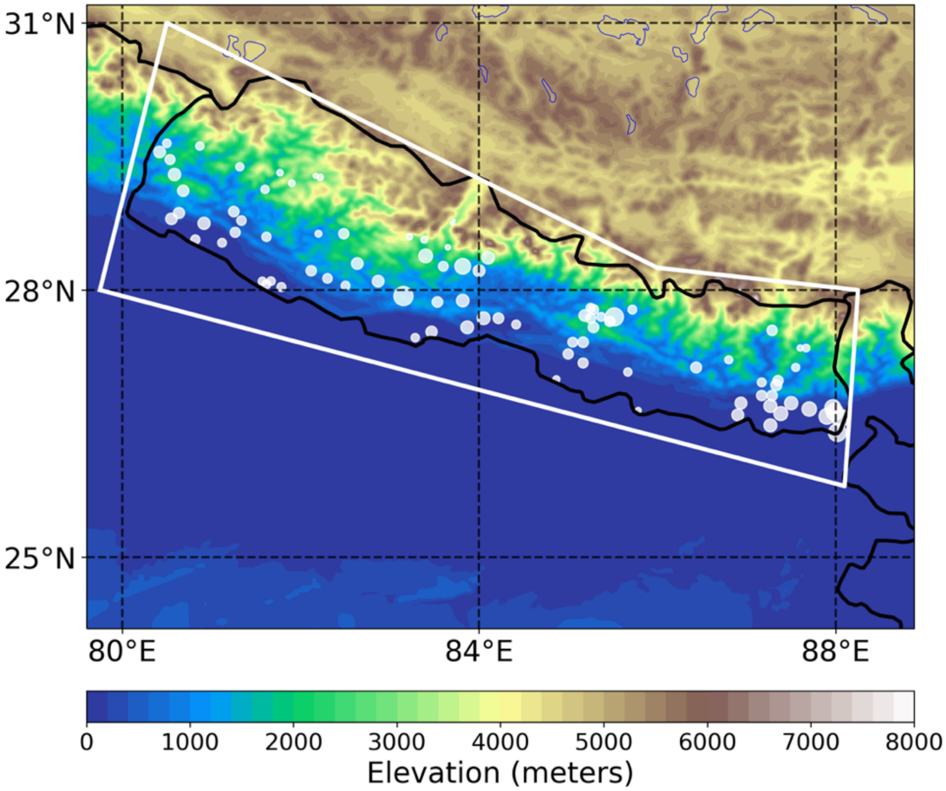


Figure: Mean precipitation distribution at the rain gauge stations evaluated in this study. The size of the dot (small to big) represents the mean precipitation in increasing order.

Reviewer #2:

General comments:

The Himalayan ecosystem has been of immense interest to scientists today for its great role in weather pattern of the region wherein millions of people in particular the mountain farmers are directly affected from the extreme and unpredictable weather. Rainfall in particular has been drastically affected in the region. Several have studied and presented results pertaining to the connection of aerosols with rainfall pattern. This study also presents much similar results with an attempt to focus additionally on the elevation-dependent rainfall. While the focus is more on the simulated results, the selection of appropriate PBL scheme, and model evaluation vaguely presented and no discussion on altitudinal profile of aerosols in the region. How appropriate it may be to compare with the AOD of cloud-free conditions. Dealing with uncertainty is a great deal in such studies even then uncertainties arising from rain data, model evaluation, boundary conditions and PBL scheme could also have been focussed. The manuscript is well structured and well written. A few concerns are given below:

We appreciate Reviewer #2 for their comments and constructive feedback on the manuscript. These comments helped to improve our older version of the manuscript.

We also agree with the reviewer, and as mentioned in our text, several studies have been performed to study the aerosol-precipitation relationship. However, to the best of our knowledge, none of the studies have been conducted to investigate the elevation-dependence of the aerosol-cloud-precipitation relationship over the complex topographical region of the Central Himalayas. In this study, we have explored the impact of aerosols on the elevational-dependent precipitation over the Central Himalayas, which has very important implications in terms of hydroclimate. Using a cloud-resolving scale and model configuration, we have performed a detailed analysis in a region with strong horizontal and vertical elevational gradients and quantified the impact of aerosols on precipitation and temperature along the elevational band. Unfortunately, the tradeoff of using cloud-resolving scales in such an expensive WRF-Chem configuration and our available computing resources is that it limited us to perform a longer simulation period and the opportunities to test the sensitivity of the results and conclusions to different model configurations around relevant processes.

Regarding the parametrization selection, we followed the schemes from different literature (including PBL) that have been adequately used to study the aerosol-cloud-precipitation relationship in similar settings around the globe. For example, similar to our study, previous studies have implemented the Morrison microphysics, RRTMG for radiation, and YSU for PBL to simulate and investigate the aerosol-cloud-precipitation interaction (turning off the cumulus parameterization) over India (Kant et al., 2021) and Sierra Nevada (Wu et al., 2018). As the convection parameterization is linked to significant sources of uncertainty in larger-scale models (Prein et al., 2015), it is recommended to use a cloud-resolving scale to assess the indirect effect of aerosols in a convective system. Furthermore, the convective parameterization was turned off for the inner 3 km domain in which the model explicitly resolves convective eddies.

For the model evaluation procedures of aerosol optical depth (AOD), we used the available datasets and platforms at hand: the MODIS (satellite) and AERONET (ground-based) AOD. Reliable data from these platforms are limited in the monsoon season because they are retrieved during cloud-free conditions. However, we evaluated the model output with the available observational datasets (both MODIS and AERONET) to gain confidence in our result. For completeness and as an effort to assess the uncertainty of anthropogenic aerosol loading, we performed additional simulations doubling the aerosol concentration and performed the analysis. As discussed in the last paragraph of section 3.4, doubling aerosol loadings resulted in the increase in heavier precipitation over the lower elevation and suppressed precipitation over the higher elevations (> 2000 m ASL) compared to the CTL (baseline) simulation and showed similar responses compared to CLEAN (reduced aerosol) simulation. Furthermore, precipitation datasets from different sources, satellite and rain gauge stations, were implemented to evaluate the model. However, some limitations still exist in the model, which we discussed in the second to the last paragraph of section 4.

Specific comments:

1. Several references are cited. Some requires critical discussion in particular.

Thank you for the feedback. We have edited and added more depth in the discussion. For example: In section 3.2 the comparison with the Napoli et al. (2022) and Wu et al. (2018) with the specific values helped support the broad statements and provide context of our results to help understand the magnitude of the differences. In section 3.3 the additional discussion with Barman and Gokhale (2022), and Adhikari and Mejia (2021, 2022) helped discuss the modulation of precipitation due to the aerosol effect in a similar complex topography setting, which helped support the findings of our simulation. Additionally, comparing the result with Napoli et al. (2022) in section 3.4 helped us provide further reasoning to the surface cooling effect. Furthermore, limitation of the study is moved to section 4, which we believe would better provide the future perspective of the study with the summary and conclusion.

2. In figure 13 (a), surface temperature is high and seen extended up to about 5000 m. The cloud fraction (figure 11) and precipitation (figure 8) do not seem to be in conformity.

   We thank the reviewer for the comments. The diurnal pattern of precipitation and cloud fraction are in conformity with each other. However, precipitation might always not follow the pattern of the cloud fraction, as the activation of cloud droplets might not always lead to the rainfall. For example, when more aerosols are activated as cloud droplets it contributes to the increased cloud fraction but might result in the suppression of precipitation as we have seen in the higher elevation of the CenHim region. This feature is further supported by the increased cloud fraction with the higher aerosol concentration leading to the enhanced activation of cloud droplets (Fig. S3).

3. Table 1 needs detailed information.

   The detailed information in the table is described in the model description (Section 2.1) and experimental setup (Section 2.2). The table shows the summarized information of the description. We have added and modified sentences for better description as follows.

   "The summary of the model configuration with the physical parameterizations used in this study is listed in Table 1. The model physics scheme used in the simulation included Morrison-double moment for microphysics, Yonsei University (YSU) for the boundary layer, Rapid Radiative Transfer Model for General Circulation Models (RRTMG) for radiation, and Unified Noah for the land surface. The double moment Morrison microphysics scheme simulates the number and mass mixing ratio of hydrometeors, including cloud droplets, rain, ice, snow, and graupel (Morrison et al., 2009). Previous studies have reasonably implemented the Morrison microphysics, RRTMG, and YSU to simulate and study the aerosol-cloud-precipitation interaction on a cloud-resolving scale (e.g., Kant et al., 2021; Wu et al., 2018). Grell-3D cumulus parameterization scheme (Grell and Dévényi, 2002) was used for the outer 9 km domain for the cumulus parameterization, while no parameterization was used for the inner 3 km domain. This consideration assumes that the model explicitly resolves convective eddies for the 3 km domain, hence the term cloud-resolving scale."

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