

Review “Influence of covariance of aerosol and meteorology on co-located precipitating and non-precipitating clouds over INdo-Gangetic Plains” Gulistan et al.

We greatly appreciate the time and effort you have invested in reviewing our work. We have carefully considered your comments and addressed your concerns, leading to improvements in the manuscript. Below are our responses to the reviewer's comments, along with indications of additions, modifications, or deletions to the text under discussion. The reviewer's comments are presented in italic black, our responses in italic green, and the text added to the manuscript in roman blue.

Referee#2 Comments

- I thank the authors for considering my comments and remarks. I believe the article is improved and ready for publication after minor revisions.

- *Thank you so much. Your appreciation is always an honor.*

1. Table 2 caption: Can the authors state in the caption that it is the median?

Reply: Thanks for the kind suggestion. The caption is revised as follows in the revised manuscript:

Table 1. Median values of meteorological parameters for PCs(NPCs) in summer and winter seasons. Maximum and minimum values for both types of clouds are shown in bold and *italic*, respectively.

2. VLOOKUP: The authors mentioned that they used the VLOOKUP function to interpolate the AOD. I am not familiar with this function, and after a search on the internet, VLOOKUP does not seem to interpolate values, it can (at best) fill in missing values.

Reply: Thanks for correction. The text is revised as follows:

The VLOOKUP function in Microsoft Excel is applied to filtering out counts where data is not available, searching for values of a parameter in the first column, and retrieving the values of other parameters in the same rows on the corresponding dates in a large dataset.

3. Can the authors explain how interpolation works?

Reply: Interpolation of satellite data is the process of estimating values between measured data points captured by satellites. Since satellite data is often collected at discrete points or intervals,

interpolation helps to create a continuous dataset by predicting values at locations where direct measurements are not available. This is commonly used to improve the resolution of the data and to fill gaps, making the data more useful for various analyses and applications such as weather forecasting, climate monitoring, and environmental studies.

However, in this study, interpolation techniques were not applied due to limitations of data and was mentioned in the manuscript mistakenly.

4. The low cloud is only liquid. I completely agree with the authors. However, I think it would help the reader if it was explicitly mentioned in the text that low-level clouds are liquid.

Reply: Thank you so much. The valuable suggestion is incorporated in the text in line no. 92-94 of the introduction section of the revised manuscript as follows:

Therefore, the present study aims to deepen the previous study (Anwar et al., 2022), by focusing on the ACPI for low-level **liquid** clouds.

The authors sincerely appreciate the valuable time, insightful feedback, and continued engagement of the esteemed reviewer with our manuscript, based on your input and useful comments, the quality of the manuscript is improved significantly.

Referee #3 Comments

The present study analyzed the response of liquid clouds, including PCs and NPCs in winter and summer to aerosol loadings in six various cities over the Indo-Gangetic Plains (IGP) under a variety of meteorological conditions. The dataset used include the long-term 21 (2001-2021) retrievals from Moderate Resolution Imaging Spectroradiometer (MODIS), Tropical Rainfall Measuring Mission (TRMM), and National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis-II datasets. The authors attempted to

quantify the ACPI by investigating the covariance analysis methods between meteorology, AOD and cloud properties.

The methods are not novel, but the findings are not convincing to me, and further clarification and discussion are needed before recommending its acceptance.

Reply: We appreciate the insightful review of the manuscript and the concerns regarding the novelty of our methodology and findings. While we acknowledge that the methodology is not completely novel, however, this study presents several unique and convincing findings that have not been addressed in previous research. A few of these findings, along with the innovative aspects of our methodology, are outlined below:

IGP is uniquely significant for aerosol and cloud studies due to its high population density, extensive agricultural activities, and rapid industrialization. The unique meteorological conditions, including the monsoon system and seasonal variations, provide a natural laboratory for observing how aerosols influence cloud formation, precipitation patterns, and atmospheric dynamics. However, to date, none of the studies reported such a long-term and comprehensive analysis using both satellite observations and reanalysis data distinguishing between precipitating and non-precipitating clouds across this region which is heavily impacted by human activities. Additionally, this study presents several unique and convincing findings that have not been addressed in previous research. A few of these are outlined below:

- *A decadal decrease in aerosols is observed over the coastal city, Karachi, and the less industrialized city, Jaipur. Whilst the increase in high percentage is observed over Ghandi College.*
- *The high frequency of cloudy days and precipitating clouds observed over Ghandi College in the summer season indicates a higher moisture content in the atmosphere during the summer at this location, leading to more cloud formation and precipitation.*
- *Values of CF for low-level clouds (both PCs and NPCs) were found to be higher during the winter season. This can be due to lower temperatures and increased atmospheric stability*

- *Whilst the favorable meteorological conditions such as higher temperatures and increased humidity, lead to more convection and cloud formation, resulting in higher precipitation rates in the summer season.*
- *During summer, Karachi experienced the most stable meteorological conditions ($LTS=15.9\pm 0.87$ K), resulting in less precipitation.*
- *While Ghandi College exhibited the most unstable conditions ($LTS=9.6\pm 0.4$ K). Ghandi College's low LTS values suggest it experiences more turbulent and convective weather, leading to more cloud formation and precipitation.*
- *AOD exhibited a strong correlation with CER for PCs. A strong correlation between AOD and CER in PCs suggests that aerosols influence the microphysical properties of clouds, affecting droplet size and precipitation processes.*
- *Similarly, the good correlation of AOD with CDNC in NPCs indicates that aerosols play a significant role in cloud formation and characteristics, affecting cloud reflectivity and lifetime.*

The major concern and comments are listed as below:

Major comments:

1. It occurs to me that there are not definitions for the PCs and NPCs in this manuscript, which are of greater importance to the results interpretation. Also, the motivation for this comparison analysis is suggested to be clarified. For instance, Why not focus on the warm clouds in terms of initial stage (cumulus) versus mature stage?

Reply: Thank you for your valuable feedback, insightful comments, and precious time as this led to the improvement of the manuscript. Following is the clarification/explanation. The following text is inserted in line 51 in the revised manuscript:

Precipitating clouds are thick clouds with significant vertical development and high moisture content, forming under unstable atmospheric conditions, such as cumulonimbus and nimbostratus, that produce precipitation reaching the ground. In contrast, non-precipitating clouds are typically

thin, have low moisture content, and form under stable atmospheric conditions, including cloud types like cirrus, cirrostratus, altostratus, and stratus, which generally do not produce significant precipitation (Houze Jr, 2014).

Houze Jr, R. A. Nimbostratus and the separation of convective and stratiform precipitation. In International geophysics. Elsevier. 104, 141-163, 2014.

We sincerely appreciate and acknowledge the kind suggestion of the respected reviewer to focus on the warm clouds in terms of the initial stage (cumulus) versus the mature stage. That involves the analysis of the temporal and spatial evolution of cumulus clouds from the initial into the mature stage and the investigation of associated variations in cloud properties and precipitation patterns. However, we cannot carry out this study because of data limitations. Further, as mentioned in the second last paragraph of section 1 in the manuscript, the motivation for this work is to deepen one of our recent studies (Anwar et al., 2022) through a long-term and detailed analysis including other significant meteorological parameters such as LTS, PR, and T_{850} , cloud microphysical parameter CDNC, categorization of clouds into PCs and NPCs and extension from monsoon regions of Pakistan to other locations of Indo-Gangetic Plains.

2. The caveat for the unclear definition of CP and NCP contains the seemingly contradictory results and findings: e.g., L32-35: I can not understand the findings such as: (2) The AOD-CER correlation is good (weak) for precipitating clouds (PCs) but weak for non-precipitating clouds (NPCs); (2) The sensitivity value of the first indirect effect is high for PCs and low for NPCs. As a fact of matter, the precipitation stage is less susceptible to aerosol effect compared with cloud stage. Besides, the logic behind the aerosol effect on precipitation, if any, goes like: “By radiative or microphysical effect, aerosol firstly affects the properties of clouds, thereby influencing the formation and evolution of precipitation”. I am surprised to see the above-mentioned two main findings that are out of the scope of my physical understanding for this issue. It should be clarified from the perspective of physical process.

Reply: Thank you for your concern about our results. Following is the clarification of your concerns about our results and findings:

- *The two results are interlinked as follows:*

when we say, "The sensitivity value of the first indirect effect is high for PCs," it signifies that in favorable atmospheric conditions, the moisture readily condenses on existing aerosol particles in PCs. This leads to the formation of numerous smaller cloud droplets with high concentrations. As these smaller droplets collide and coalesce, they grow to larger size. Consequently, this phenomenon results in a strong AOD-CER correlation for PCs, and a weak for NPCs.

3. Why the authors only show the results for 6 different cities over the IGP but not the overall region of IGP. As the dataset used basically are acquired from satellite, it will not be difficulty to accomplish this task. Therefore, for the benefit of readers to gain a full understanding of ACPI in this region, I strongly suggest the authors add the overall analysis over the whole region of IGP.

Reply: We appreciate the esteemed reviewer's valuable suggestion. The Indo-Gangetic Plain (IGP) is characterized by a diverse and extensive pool of aerosols due to its unique topography, making the entire region crucial for analyzing ACPI. The Himalayas to the north act as barriers to the winds, leading to the trapping of aerosols over the central part of the IGP, resulting in a high concentration of anthropogenic aerosols and creating a dense aerosol belt at the base of the mountains.

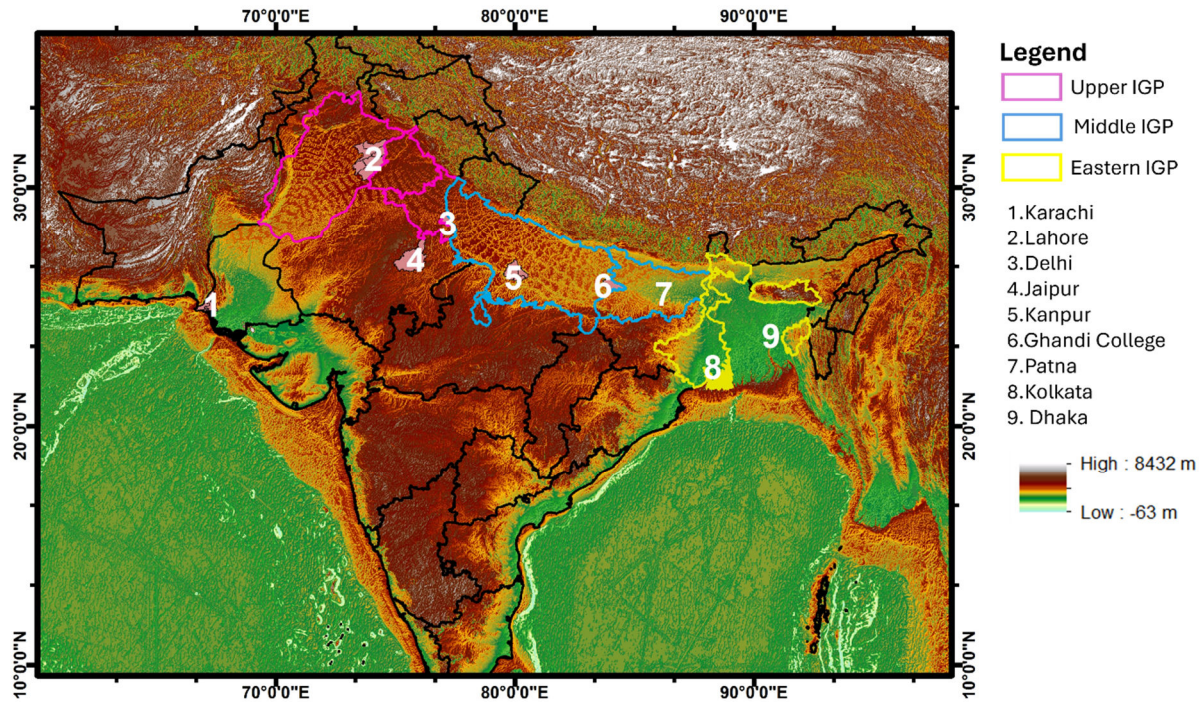
In the earlier version of the manuscript, we focused on six key locations. Following the honorable reviewer's recommendation in the first revision, we extended our study area to the eastern part of the IGP by including three additional sites. To avoid overcrowding the manuscript and due to the similarity of the results, we have documented these findings in the supplementary material, as noted in the last line of section 2.1, "Study Area."

We deeply respect the valuable feedback and kind suggestions of our esteemed reviewer to expand it further. In light of this, we plan to expand our study to encompass the southern part of the IGP in future research. We believe this will provide a more comprehensive analysis and further enrich our understanding of the region

4. Section 2.1 & Figure 1: The caption of Figure should be expanded to include more information, such as the city marked by blue dots. Besides, the legend for these blue dots

are missing. Lastly, the upper, middle, and eastern portions of the IGP are suggested to be marked on this figure.

Reply: Thanks for the comments. Per your valuable suggestion, more information is added and is inserted in the revised manuscript as follows:



5. It occurs to me that the title emphasize the contrast of aerosol impact on PC versus NPC, but there are not any key points in Highlights being specific for the aerosol impact on either PC or NPC. Why?

Reply: Thanks for pointing this out. The ‘highlights’ are accordingly revised as follows:

Strong aerosol-cloud interactions under unstable meteorological conditions led to the formation of thick precipitating clouds.

6. The English writing should be improved.

Reply: Thanks; We have tried our best.

Minor comments:

1. L19-21: RETRIEVALS can be used to describe satellite product, but not for reanalysis, and thus the authors are suggested to rephrase it.

Reply: Thanks, the valuable suggestion is implemented, and the text is revised as follows in the revised manuscript.

Therefore, this study aims to systematically investigate the effects of aerosols and meteorological factors on ACPI in the co-located precipitating (PCs) and non-precipitating clouds (NPCs) clouds in winter and summer seasons by analyzing the long-term (2001-2021) retrievals from Moderate Resolution Imaging Spectroradiometer (MODIS), and Tropical Rainfall Measuring Mission (TRMM) products coupled with the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis-II datasets over the Indo-Gangetic Plains (IGP).

2. L38-39: Does “the precipitation rate (PR) exhibits high values in summer season” have any logic correlation with “and PR values are found high in comparatively thin clouds with fewer CDNC..”?? why did the authors put these two sentences together into one sentence???

Reply: Thanks for the correction. To accommodate the comment and further clarify, the text is revised as follows in the revised manuscript:

Furthermore, the precipitation rate (PR) exhibits high values in the summer season, primarily due to the significant contribution from optically thick clouds with lower CDNC ($< \sim 50 \text{ cm}^{-3}$) and larger CER and intermediate contribution from optically thick clouds with higher CDNC ($> \sim 50 \text{ cm}^{-3}$).

3. L45-47: ACPI is generally referred to aerosol indirect effect, whereas ARI refers to aerosol direct effect. However, the authors use both terms cursively, which will make the readers and me confused. Therefore, the authors can rephrase it to make the expression more consistent throughout the whole manuscript.

Reply: Thank you for your precious time. The valuable suggestion is implemented.

4. L68: Grammatic errors in “and makes”.

Reply: Sorry for the typo and we fixed it.

5. L69-71: is “heat wave” associated with the topic investigated in this manuscript? Also, necessary references are needed to support “frequent variations in cloud fraction (CF), extreme precipitation...”

Reply: Thank you for the valuable suggestion. The clarification/explanation is as follows.

- *The interactions between aerosols, clouds, and precipitations are complex and can have varying impacts on heat waves depending on the types of aerosols, cloud properties, and regional climatic conditions.*
- *The following reference is added at the end of the sentence as follows in the revised manuscript.*

Besides, frequent variations in cloud fraction (CF), extreme precipitation, abrupt temperature changes (e.g., heat waves), and irregular unseasonal rains may cause major hazards at local and regional levels in the future (Zhou et al., 2020).

Zhou, S., Yang, J., Wang, W., Zhao, C., Gong, D., Shi, P.: An observational study of the effects of aerosols on diurnal variation of heavy rainfall and associated clouds over Beijing–Tianjin–Hebei, *Atmos. Chem. Phys.*, 20, 5211-5229, <https://doi.org/10.5194/acp-20-5211-2020>, 2020.

6. L72-73: Some important work in the literature is missing for the ACI from observations, including but not limited to: <https://doi.org/10.1126/science.1089424>; <https://doi.org/10.1016/j.atmosenv.2015.04.063> ; <https://doi.org/10.1029/2019GL085442>.

Reply: Thank you for suggesting very informative and valuable research work. To accommodate the kind suggestion, we added this and a few more references in the revision as follows::

In the last two decades, the scientific community has focused on the quantification of ACI using both observations (Feingold et al., 2003; Koren et al., 2004; Costantino et al., 2010; Wang et al., 2015; Zhao et al., 2018, Guo et al., 2019; 2020; Anwar et al., 2022)

Guo, J., Su, T., Chen, D., Wang, J., Li, Z., Lv, Y., Zhai, P.: Declining summertime local-scale precipitation frequency over China and the United States, 1981–2012: The disparate roles of aerosols. *Geophys. Res. Lett.*, 46(22), 13281-13289, <https://doi.org/10.1029/2019GL085442>, 2019.

Koren, I., Kaufman, Y. J., Remer, L. A., & Martins, J. V.: Measurement of the effect of Amazon smoke on inhibition of cloud formation. *Sci.*, 303(5662), 1342-1345, <https://doi.org/10.1126/science.1089424>, 2004.

Wang, F., Guo, J., Zhang, J., Huang, J., Min, M., Chen, T., Li, X.: Multi-sensor quantification of aerosol-induced variability in warm clouds over eastern China. *Atmos. Envi.*, 113, 1-9, <https://doi.org/10.1016/j.atmosenv.2015.04.063>, 2015.

7. L98: w rather than Ω , is used to represent vertical velocity.

Reply: Thank you. The good suggestion is implemented.

8. There are too many grammar errors or inappropriate expressions throughout this manuscript, and I strongly suggest the authors find the help to touch up this work, at least from the perspective of English writing. Sorry that I can not be more positive at the current stage.

Reply: Thank you. We have tried our best and got professional help with English.

We would like to extend our sincere gratitude to the esteemed reviewer for their insightful and constructive feedback. Based on your constructive comments, the quality of the manuscript is significantly improved.
