Reply to first reviewer on review of "Influence of covariance of aerosol and meteorology on co-located precipitating and non-precipitating clouds over Indo-Gangetic Plains" Gulistan et al.

We are very thankful to the anonymous referee for his/her expert opinion on our work which leads to the improvement of the manuscript. Below are the replies to the reviewer's comments, and indications of additions, modifications, or subtractions to the text under discussion. ***We report the reviewer's comments in italic red, our responses in italic black, and the text added to the manuscript in roman Blue.***

1. *The paper asserts that the high loading of aerosols led to a high occurrence of precipitating clouds in summer. While high PR values in summer seem to have some associations with aerosols, the presentation seems to skirt around establishing a firm causality. Is it possible that some factors that influence both aerosols and precipitation simultaneously? Thus, this study may need to discuss the cause-and-effect relationship outlined in the study's conclusion.*

Reply: *We are thankful to the respected reviewer for constructive and insightful comments. In the revised manuscript we have discussed the meteorological parameters which may have significant implications on aerosols and precipitation formation. We also agree to discuss the cause-and-effect relationship outlined in the conclusion. For this reason, the following paragraph is inserted in the revision of the manuscript in the fourth line of section 3.4.3:*

The stable atmospheric condition with high LTS value in winter serves to inhibit the convection process and have a significant impact on controlling the PR in winter (Zhao et al., 2006). Conversely, during summer season, the meteorological instability prevails with low LTS values which result in high RH. This not only causes enhanced AOD due to the water uptake and resulted swelled hydrophilic aerosols (Alam et al., 2010; Alam et al., 2011) but also affects the cloud and precipitation formation due to the enhanced evaporation and convection. Additionally, Fig. 8-9 also show evidently and specifically during summer that the possible cause of positive AOD-CER correlation is the negative AOD-CDNC correlation under unstable meteorology over all areas except Karachi. As a result, Fig. 11 shows high (low) values of PR over all areas with maximum over Gandhi College (Karachi).

2. *The discussion may have a discussion of the uncertainties tied to the satellite datasets used in this study, as well as how the uncertainties may influence the AOD-CER correlation and the SIE.*

Reply: *We are grateful to the reviewer for very nice comments on our manuscript. Yes, we agree that due to remote sensing nature, satellite retrievals have uncertainties which propagate to our results and findings and cause uncertainties in prediction of climate change. In this regard, to discuss the uncertainties in satellite retrievals and its propagation to AOD-CER and SIE, the following paragraph is inserted in the revised manuscript at the end of section 3.4.1:*

Recent advances in remote sensing led to cost-effective solutions and an increase in available data at various temporal and spatial resolution to bridge scientific gaps among different disciplines. While satellite-based retrievals have many advantages over in-situ and ground-based measurement such as broader regional coverage and enhanced spatial resolution, they are still prone to considerable uncertainties owing to the indirect nature of remote-sensing, retrieval algorithms, thermal radiance, infrequency of satellite overpasses, and cloud top reflectance (Hong et al., 2006; Tian et al., 2010; Hossain et al., 2006). In our study, apart from the aforementioned factors contributing to the uncertainty, any residual cloud contamination could also lead to biased retrieval of AOD. Likewise, satellite-based retrievals for cloud properties are crucial to understanding the pivotal role of clouds in climate and the role of clouds is still a dominant source of uncertainty in prediction of climate change. These, uncertainties in AOD and retrievals of cloud properties also propagate through the modeling process, potentially leading to less accurate climate predictions. Likewise, these uncertainties appeared to influence the findings in the current investigation. For instance, a limited correlation between AOD and CER is observed over Lahore, particularly in cloudier regimes as depicted in Fig. (5-6). This contrasts with robust impacted documented in the earlier studies (Michibata et al., 2014). However, high sensitivity of SIE is observed for PCs particularly in winter season indicating the delay in onset of precipitation and more retention of clouds.

3. *The study only considers a few locations, limiting the scope of the conclusions. The authors should discuss the implications of the relationships between clouds, aerosols, and precipitation over Indo-Gangetic Plains for other regions. For example, whether the high sensitivity value of the FIE in winter can be established to other regions.*

Reply: Thank you for the detailed and useful comments. Following the suggestion, we have expanded the study to the eastern part by investigating Kolkata, Dhaka and Patna and covered the full Indo-Gangetic Plains. For complete investigation of ACPI over Kolkata, Dhaka and Patna, including the decadal and seasonal variations in aerosols, seasonal variations in meteorological parameters for PCs and NPCs, occurrence of *cloudy days and PCs, cloud types, influence of AOD on CER and CDNC at different atmospheric stability for PCs and NPCs in both summer and winters, indirect effects (FIE, SIE and TIE) and ACI for PCs and NPCs in summer and winter. Since, the number of figures increases significantly, we document the results for the eastern part as supplementary material. And as a result, in the revised manuscript the map of the study area is updated as follows.*

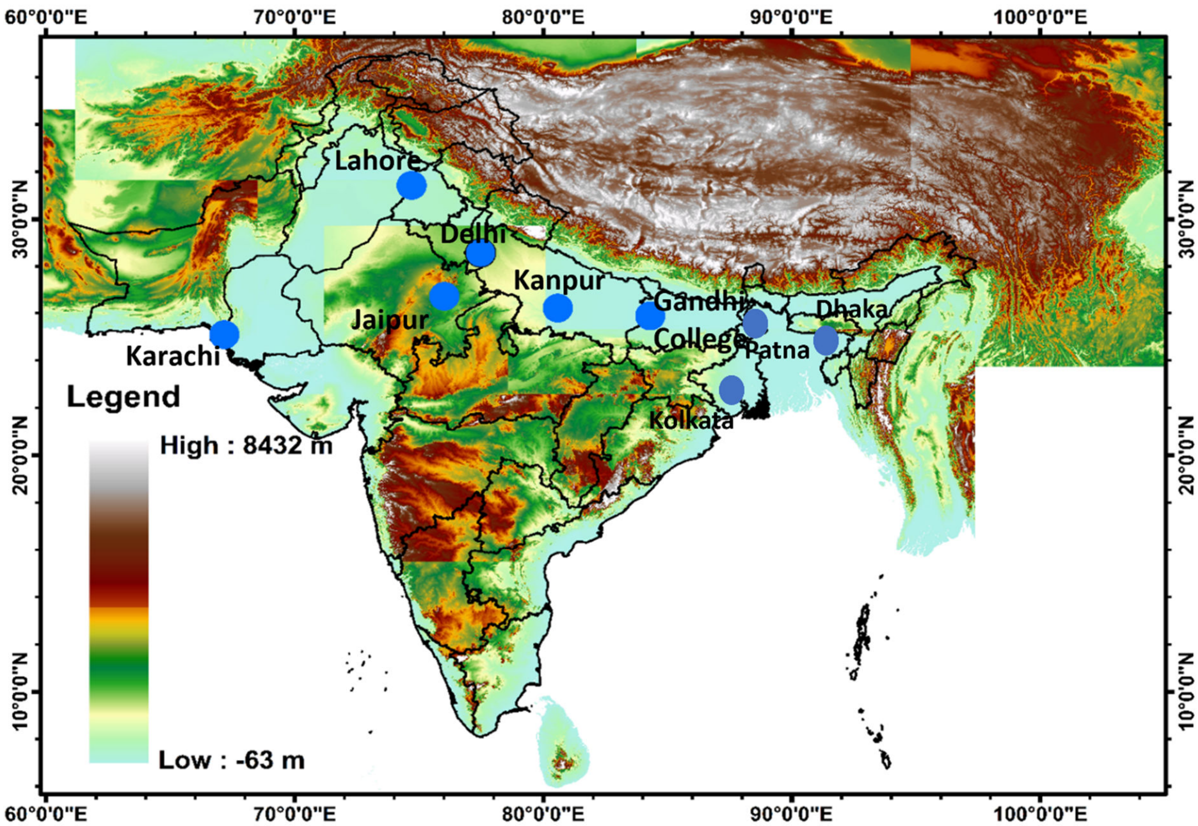

Fig. 1. Topography of the study area.

- *The following results for Kolkata, Dhaka and Patna are documented as supplementary material.*

Table 1S. Decadal percentage variations in average values of AOD over eastern part of IGP

	Kolkata	Dhaka	Patna
Total number of counts	1976	2018	2629
Decadal change in AOD	18%	22.6%	23.3%

Table 1S shows the decadal change in AOD over Kolkata, Dhaka and Patna. Similar to Gandhi College, an increase is observed over all the three areas. Reason for the increase of aerosols include multiple sources of aerosols, human behavior, socio-economic development at local and regional level, and unique topography for persistence and retaining of aerosols.

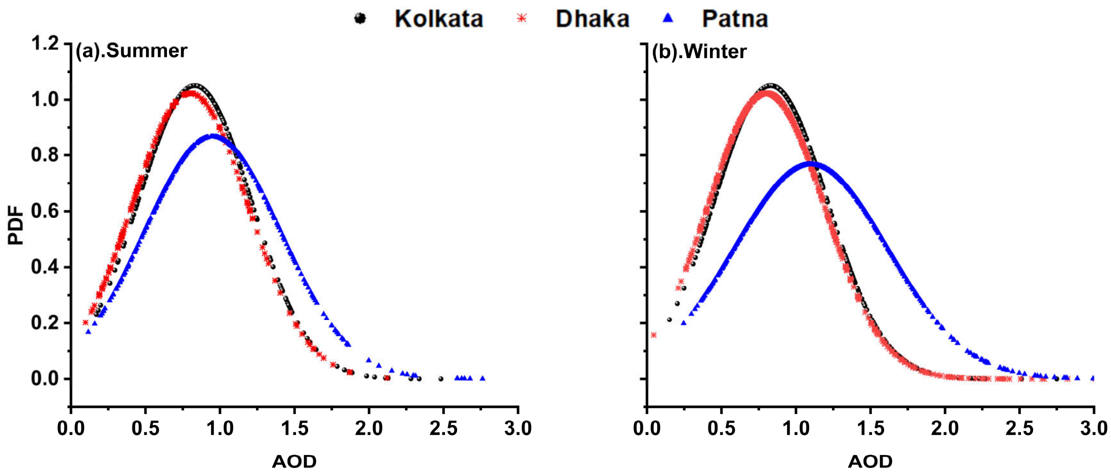

Fig. 1S. Probability density function (PDF) of AOD over study sites is shown (a) and (b) for summer and winter seasons respectively.

Fig. 1S shows the seasonal PDF values of AOD over all the three areas. The results indicate similar seasonal distribution functions. In both seasons PDF peaks for high values of AOD are observed over Patna showing high concentration of aerosols as compared to Kolkata and Dhaka.

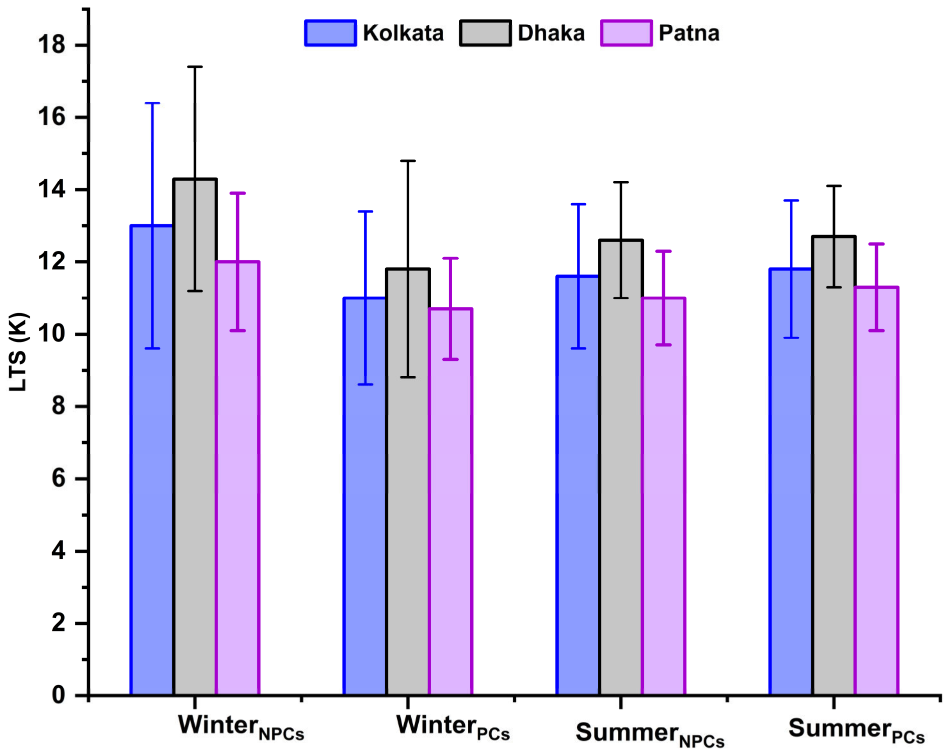

Fig. 2S. Variations in lower tropospheric stability (LTS) over all study sites for PCs and NPCs in winter and summer seasons, the error bars show the standard deviation (SD) values.

Fig. 2S and Table 2S show the LTS conditions for PCs and NPCs. The high LTS values indicate more stable condition over Dhaka. Similarly, Table 2S shows the seasonal average values for other meteorological parameters. The results indicate high values of T_{850}, RH% and Ω over Patna in summer.

Table 2S. Meteorological parameters for PCs(NPCs) in summer and winter seasons. Maximum values are for both types of clouds shown in bold and minimum values are indicated as italic.

	Winter Season			Summer Season		
	T_{850} (K)	RH%	Ω (m/s)	T_{850} (K)	RH%	Ω (m/s)
Kolkata	**286.4±1.9** (**286±1.86**)	53.9±22.5 (*42±14.5*)	*0.004±0.1* (***0.08±0.09***)	*295.7±1.6* (295.7±1.8)	*70.3±12.5* (*67.7±15.6*)	-0.15±0.07 (-0.14±0.07)
Dhaka	286.2±1.5 (*285.2±1.9*)	*51.8±14.5* (50.9±13.8)	*0.03±0.09*(0.07±0.1)	*294.6±1.1*(*294.6±1.2*)	*76.3±7* (*75.9±8.4*)	*-0.13±0.07* (*-0.1±0.08*)
Patna	*284.4±1* (*284.3±2.4*)	**67.7±15.3 (56.6±13.9)**	-**0.07±0.13**(*0.04±0.0.12*)	**297.5±1.1(297.5±1.4)**	**82.1±16.8(76.3±19.7)**	***-0.2*±0.1 (*-0.17*±0.1)**

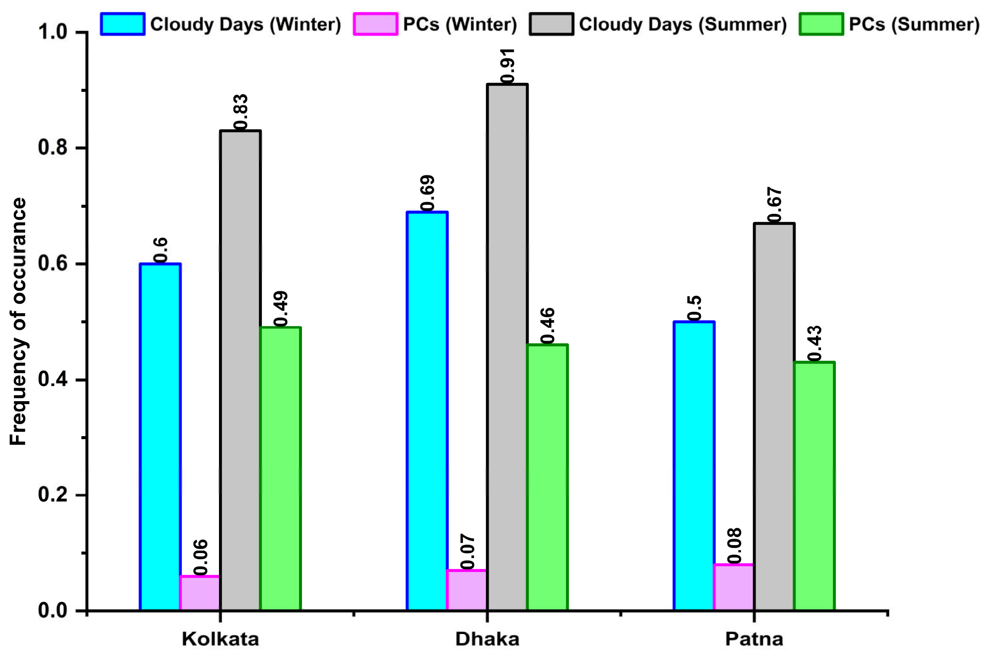

Fig. 3S. Frequency of occurrence of total cloudy days (including PCs and NPCs) and only PCs is shown for both winter and summer seasons.

Fig. 3S shows the total number of cloudy days and the number of days on which PCs occurred. The high occurrence of clouds is observed over Kolkata and Dhaka in both summer and winter seasons. The high occurrence of PCs in summer is due likely to the significant impact of elevated aerosols with the southwesterly winds on the summer monsoons and occurrence of PCs. Therefore, Kolkata and Dhaka are of critical importance from perspective of aerosol loading and ACI (Dahal et al., 2022).

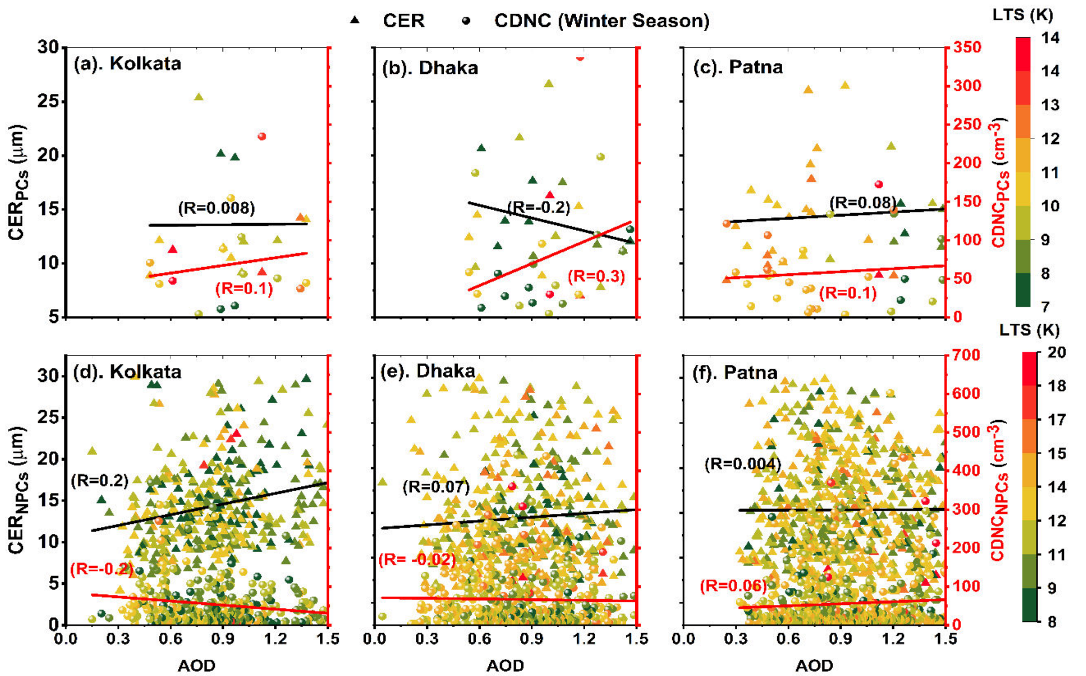

Fig. 5S. AOD-CER and AOD-CDNC correlation coefficient for PCs and NPCs over all study areas in winter season.

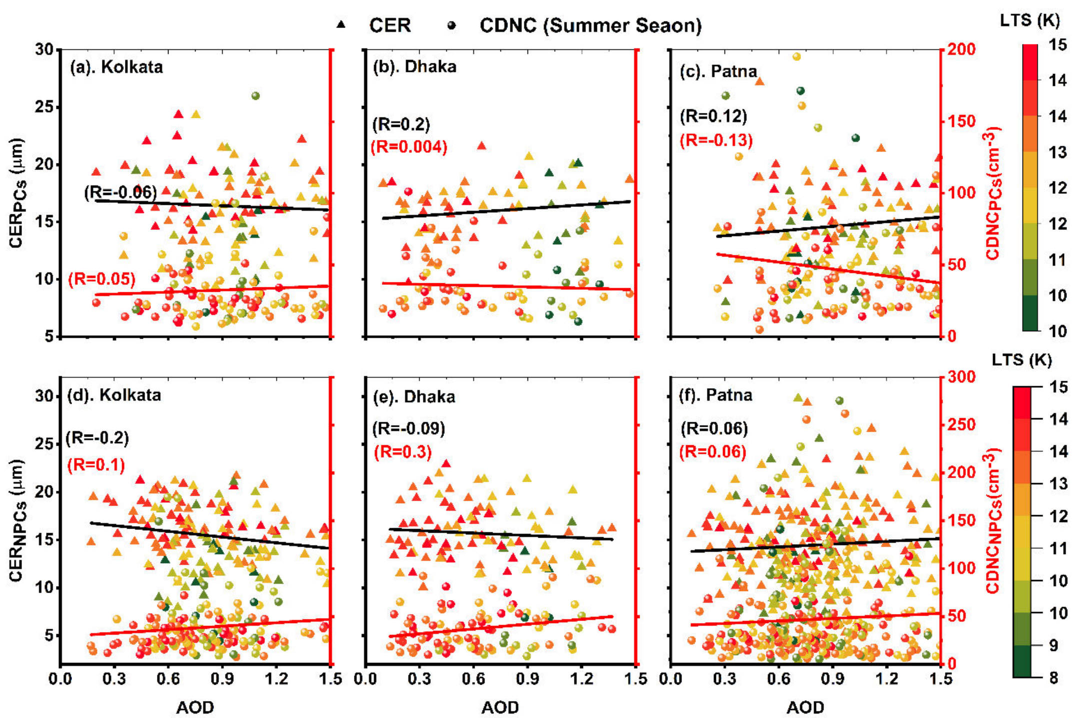

Fig. 6S. Same as Fig. 5S but in summer season.

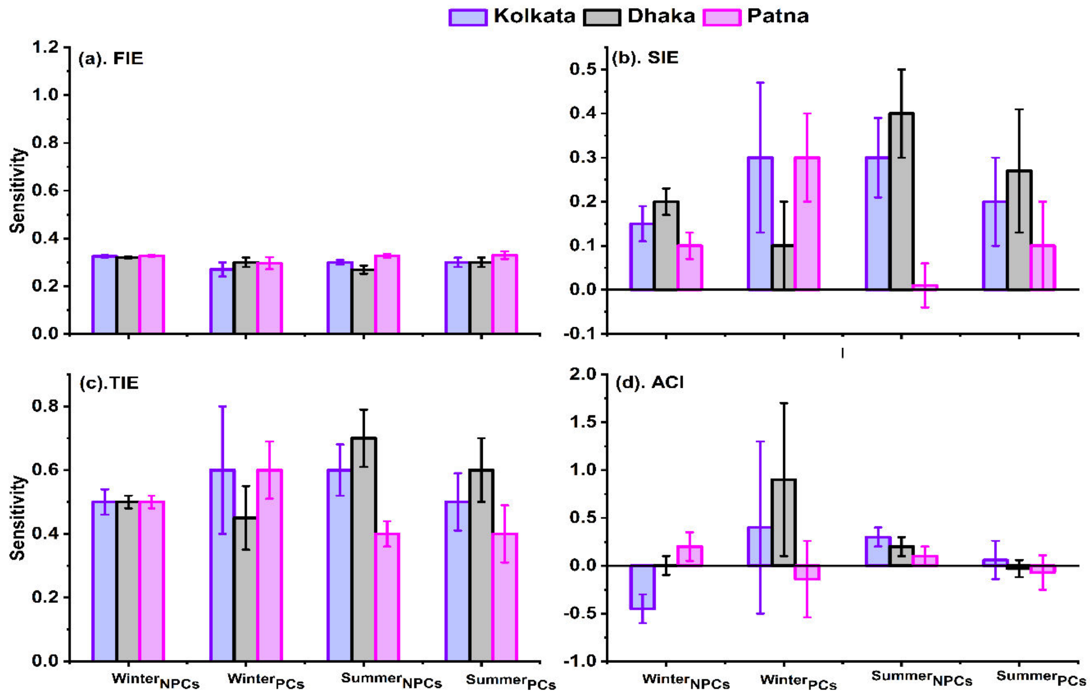

Fig. 7S. The sensitivity metrices estimated for aerosol-cloud relationship using CDNC is shown in (a) FIE , (b) SIE, (c) TIE and (d) ACI.

Fig. 5S and 6S show the impact of AOD on CER and CDNC for PCs and NPCs in winter and summer respectively. The results indicate a positive and weak AOD-CER correlation for NPCs over all areas and for PCs over Kolkata and Patna in winters. Similarly, a positive and weak AOD-CDNC is observed over all areas for PCs. Likewise, Fig. 6S also illustrates weak correlation for both types of clouds in summer. As compared to other areas, the correlation analysis is less significant over Karachi, Kolkata, Dhaka and Patna. This can be attributed to the persistence of diverse aerosol types influenced by their coastal locations, different meteorology and the alternating inflow and outflow of easterly and westerly winds.

Fig. 7S(a) shows sensitivities for FIE in both seasons for PCs and NPCs. The results indicate high values of sensitivity FIE in winter season which is similar to the results for Karachi, Lahore, Delhi and Kanpur as shown in Fig. 10 a. This is attributed to high level of aerosol emission from residential heating and industrial activities. Furthermore, the results illustrate higher values of FIE in summer. This is attributed to the massive aerosol loading due to aerosol carried by winds and originated by anthropogenic activities and unstable meteorology.

4. *Although the manuscript mentions "the complications of aerosol-cloud-precipitation interactions over complex topography," it doesn't sufficiently explain how specific topographical features impact the ACI. A further discussion of potential topography impacts may strengthen the paper.*

Reply: *We are thankful to the reviewer for the detailed review of our manuscript. The unique topography of IGP influences the persistence of aerosols transported by the prevailing winds which influenced the ACI significantly. Therefore, following text is added at line 179 to discuss the impact of potential topography:*

IGP characteristically exhibits a diverse and massive pool of aerosols due to its unique topography. The western part of IGP is a coastal location and inlet for the westerly winds. Therefore, dry regions and Arabian sea in the west contribute dust, sea salt and water vapors to the region. The Himalayas in the north act as barriers to the winds, leading to the trapping of aerosols over the central part of IGP. Therefore, this region exhibits a high concentration of anthropogenic aerosols. Bay of Bengal in the east allows southeasterly winds to enter passing across Dhaka, Kolkata, Patna to Delhi and Lahore (Hassan et al., 2002; Anwar et al., 2022). The westerly and easterly winds traverse forested hilly terrain, rivers and lakes elevating humidity level and initiate the cloud formation by activation of the newly originated small aerosol particles as CCNs and cloud formation affecting the local microclimate.

References

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