

***Impact of aerosol absorption and scattering on winter fog lifecycle:
Insights from NWP simulations over Indo-Gangetic Plains***

Reviewer 2

General Remarks

This manuscript examines how aerosol absorption and scattering influence the winter fog lifecycle over the Indo-Gangetic Plains using DM-Chem1.0 sensitivity experiments for 1–10 January 2023. The topic is important, and the attempt to separate absorbing and scattering components of aerosol-radiation interactions within an operational fog-forecasting framework is useful. At the same time, some conclusions appear stronger than the current evidence supports, and the paper would benefit from clearer positioning relative to recent IGP studies, more cautious interpretation of the sensitivity experiments, and a fuller discussion of observational and model uncertainties.

General Response: We sincerely thank the reviewer for this balanced and constructive assessment. We are encouraged that the reviewer recognises the importance of the topic and the utility of separating absorbing and scattering aerosol-radiation interactions within an operational fog-forecasting framework.

We have revisited the concluding statements and moderated the statements that may have appeared stronger.

We have expanded the introduction and discussion sections to more explicitly situate our findings within the growing body of literature on aerosol-fog interactions over the Indo-Gangetic Plains. We acknowledge that several recent studies have examined aerosol-radiation feedbacks in this region, and we have taken care to highlight both where our results corroborate and where they extend or differ from prior findings.

We have added text acknowledging the limitations associated with the short simulation period, observational constraints, and uncertainties related to larger regional-scale meteorological controls.

We hope that the revised manuscript adequately addresses the reviewer's concerns.

Specific comments:

#1. The novelty should be stated more clearly and placed better in the context of recent aerosol-fog studies over the IGP. Previous work has already shown that aerosol-radiation feedback and absorbing aerosols can affect fog timing, intensity, and spatial structure.

The main contribution here seems to be the explicit separation of absorption and scattering effects within DM-Chem, and the authors should make this distinction clearer.

Response: Yes, the reviewer has rightly mentioned the highlight of the present work and, and relevant text has been edited/added in the revised manuscript to bring out the contribution of the study more clearly.

The Introduction section now includes additional context of some earlier studies and the present work is now positioned against the backdrop of these studies.

[Ln 57-87 of the revised manuscript]

High aerosol loading in the IGP plays a crucial role in the growth, sustenance, and dissipation of fog both through ACI and ARI. Early observational studies (Das et al., 2008) in the IGP established that increasing aerosol optical depth, decreasing surface temperatures, and higher relative humidity collectively favour fog formation. The role of ACI in fog microphysics has been relatively well studied with several studies reporting a strong positive influence of ACI on fog lifecycle (Maalick et al., 2016; Boutle et al., 2018; Yan et al., 2021; Bharali et al., 2024).

In comparison, the role of ARI has received relatively less attention. However, the IGP is characterized by high aerosol loading during winter, including significant concentrations of absorbing aerosols such as black carbon and brown carbon arising from fossil-fuel combustion, biomass burning, and crop-residue burning. However, recent observations indicate a rising trend in absorbing aerosols across the region (Thomas et al., 2019; Ramachandran and Rupakheti, 2022). The impact of these aerosols is evident in both urban and rural settings: Gautam and Singh (2018) demonstrated the presence of "fog holes" over urban centres, likely driven by the urban heat island effect, while Anurose et al. (2024) reported similar fog-clearing patterns over rural areas attributed to radiative heating by absorbing aerosols through ARI. These findings collectively highlight that aerosols significantly modulate fog processes in the IGP, both directly (ARI) and indirectly (ACI), making the region a natural laboratory for investigating aerosol effects on fog dynamics.

The IGP region has both industrial centres as well as densely populated cities with high vehicular traffic. The region remains a hotspot of black carbon, though some studies report a decreasing trend (Abdullah et al., 2025; Mehrotra et al., 2024). In addition to this, several studies have also reported significant brown-carbon absorption over the IGP, especially during winter, foggy episodes, biomass/crop-residue burning periods, and regional outflow events (Choudhary et al., 2024; Navinya et al., 2025; Shamjad et al., 2015). Hence, it becomes important not only to study the role of ARI in fog lifecycle but

also to examine the relative contribution of aerosol absorption and scattering in a polluted region like the IGP to fog responses.

With this background, the present study is aimed at understanding the influence of aerosols, particularly ARI, on fog over IGP using numerical modelling with a focus on dense fog conditions. The experiments have been designed to isolate the absorbing and scattering components of ARI within the same modelling framework, thereby allowing their relative roles in the temporal evolution, spatial extent, vertical development fog to be assessed. The findings may help provide a more process-level understanding of how different radiative properties of aerosols modulate fog evolution in IGP-like environments. Such understanding can support better-informed decision-making to regulate particulate matter pollution and mitigate the associated social and environmental impacts of dense fog.

Further, in section 4 (Conclusions and Discussions), the results of the present work are compared with those of some earlier similar studies [Ln 384-404 of the revised manuscript], and the distinction of the present work with regard to the separation of absorption and scattering effects has been mentioned .

The major inference that can be drawn from the simulations conducted in this study is that while aerosol availability is crucial for initiating fog formation, the absorbing and scattering components of ARI significantly influence subsequent fog growth, maintenance, and dissipation. The findings in this study contrast with those of Yan et al (2021), who reported that ARI has a negligible effect on fog lifetime in East China. However, some studies suggest that ARI plays an important role in heavily polluted environments. Ding et al. (2019) found that the effect of ACI was weaker than that of ARI on the formation and evolution of fog during a haze pollution episode in the Yangtze River Delta region in eastern China. This aligns with broader modelling evidence from Liu et al (2020), who reported that ACIs tend to saturate at high aerosol loading, whereas the strength of ARIs continues to increase and plays a more important role in highly polluted episodes. Although Liu et al (2020) examined the impact of biomass burning aerosols on clouds and precipitation in the Amazon basin rather than fog directly, they noted that this behaviour should extend to other light-absorbing aerosols such as fossil fuel combustion aerosols in industrialized and densely populated areas. Peng et al (2022) also noted that ARI has a critical influence on the outbreak of severe haze-fog by virtue of reducing surface solar radiation, which further leads to weakened turbulence, reduced temperature, and increased humidity favouring hygroscopic growth of aerosols.

Specifically, over the IGP region, Bharali et al. (2024) also drew a similar inference from their investigation of a dense fog episode that the aerosol–radiation feedback plays an important role in the intensity and lifetime of fog. Arun et al (2025) used the WRF-Chem model to conduct a suite of experiments to assess the relative importance of ARI and ACI in the over IGP region. They concluded that ACI is the dominant pathway in fog formation while ARI influences surface stagnation, cooling, and moistening, thereby affecting fog persistence and dissipation. In the present study, we further examined the relative roles of the absorbing and scattering components of ARI and found that aerosol absorption appears to play an important role in the study region, as also noted by Anurose et al. (2024). The AAI values, which indicate a considerable presence of absorbing aerosol types, support the aerosol environment represented in the model and lend credibility to experimental focus on aerosol absorption in the context of the IGP region.

#2. The experimental design is useful, but some conclusions should be phrased more cautiously. The AI experiment and the ARII experiments are idealized sensitivity tests, and they do not directly represent realistic emission-control or policy scenarios. The authors should clarify how the aerosol reductions were applied, and avoid implying that the results quantify a real-world source-response relationship.

Response: Reductions in emissions in the AI experiment were applied such that the resultant PM_{2.5} concentrations were minimal indicating a clean environment. This was done as a part of sensitivity analysis to understand fog response. This is not to be considered as an analysis for a potential pollution-control scenario. The objective of this experiment is clarified in Ln 110-116 of the revised manuscript

..... A series of experiments was designed to primarily investigate the impact of ARI on fog formation and evolution. First, a control simulation was performed using the operational version of DM-Chem1.0 (Control). Subsequently, before examining the impact of ARI, a simulation was conducted to assess the influence of aerosol concentration on fog evolution (Aerosol Impact, AI). For this purpose, input emissions of key aerosols and aerosol precursors (sulphate, organic matter, black carbon, H₂O₂, DMS, SO₂, DMSO, monoterpene, sea salt), were reduced by a factor of 10³ to mimic near-pristine conditions (Yan et al., 2021). The resulting near-surface PM_{2.5} concentrations remained below 5 µgm⁻³, confirming a clean environment.

Further, the intended application of this study has been clarified in the Introduction section to highlight how the findings of the study can support decision-making for pollution mitigation strategies rather than providing emission-control or policy scenarios.

[Ln 81-87 of the revised manuscript]

....the present study is aimed at understanding the influence of aerosols, particularly ARI, on fog over IGP using numerical modelling with a focus on dense fog conditions. The experiments have been designed to isolate the absorbing and scattering components of ARI within the same modelling framework, thereby allowing their relative roles in the temporal evolution, spatial extent, vertical development fog to be assessed. The findings may help provide a more process-level understanding of how different radiative properties of aerosols modulate fog evolution in IGP-like environments. Such understanding can support better-informed decision-making to regulate particulate matter pollution and mitigate the associated social and environmental impacts of dense fog.

#3. The observational and model evaluation should be strengthened. The current evaluation relies mainly on visibility at one airport and a limited LWP comparison, while the spatial structure of modeled LWP and fog may not be fully consistent with observations. It would also help to present the aerosol absorption datasets as supporting evidence rather than direct validation of the simulated ARI response.

Response: DM-Chem1.0 is the operational model at the National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, India, for forecasting of fog and particulate matter. Performance evaluation of the model has been demonstrated in detail in Jayakumar et al, 2025 for the period of 1-31 January 2023, and the time period of the present study (1-10 Jan 2023) is a subset of that and was chosen based on maximum incidences of dense fog events. Further, the previous version of DM-Chem model has also been validated in Jayakumar et al, 2021.

We do concur that the spatial heterogeneity in LWP is not reproduced well by the model when compared with MODIS. Nonetheless, we can deduce from Fig. A1 that the spatial coverage of fog is similar, which is itself a challenge in NWP models for fog. The lower modelled LWP is consistent with the earlier fog dissipation seen in Fig. 1b, particularly because MODIS retrievals are limited to daytime (~0930–1100 IST). The relevant line has been suitably revised as follows to interpret Fig. A1 more cautiously [Ln 154-156 of revised manuscript]:

..... Further, comparison with the MODIS (Terra) satellite product for a dense fog day in the study period (7th Jan 2023) suggests that the model reasonably captures the spatial extent of fog, as reflected in the cloud liquid water path (LWP) distribution shown in Fig. A1 of the Appendix.

Further, rather than indicating that the presence of absorbing aerosols validates our model results, we note that an appreciable presence of absorbing aerosols in the IGP domain supports the framework of our study.

[Ln 399-404 of revised manuscript]

..... *In the present study, we further examined the relative roles of the absorbing and scattering components of ARI and found that aerosol absorption appears to play an important role in the study region, as also noted by Anurose et al. (2024). The AAI values, which indicate a considerable presence of absorbing aerosol types, support the aerosol environment represented in the model and lend credibility to experimental focus on aerosol absorption in the context of the IGP region.*

The relevant line in the abstract has also been revised [Ln 18-19]:

..... *Satellite-derived absorbing aerosol indices confirmed the presence of absorbing aerosols over the study region.*

[Ref: Jayakumar et al. (2025). Development of an Integrated Modeling Framework for Visibility and Air Quality Forecasting in Delhi. *Bulletin of the American Meteorological Society*, 106(2), E261-E274. <https://doi.org/10.1175/BAMS-D-24-0194.1>
Jayakumar et al. (2021) Delhi Model with Chemistry and aerosol framework (DM-Chem) for high-resolution fog forecasting. *Q J R Meteorol Soc*, 147(741), 3957–3978. <https://doi.org/10.1002/qj.4163>

#4. The interpretation of aerosol effects needs clearer separation between ACI and ARI. The results suggest that aerosols are important for fog formation mainly through their role as CCN, while ARI modifies fog growth, depth, and dissipation. The authors should avoid wording that gives the impression that ARI is the primary driver of fog formation, and should clarify the relative roles of ACI, absorption, and scattering.

Response: Following the reviewer’s suggestion, a more cautious approach is taken towards wording of the conclusions

[Ln 384-386 of revised manuscript]

The major inference that can be drawn from the simulations conducted in this study is that while aerosol availability is crucial for initiating fog formation, the absorbing and scattering components of ARI significantly influence subsequent fog growth, maintenance, and dissipation.

This is followed by a comparison with findings from other similar studies to deduce how the heavily polluted conditions in IGP might be behind an important influence of ARI via aerosol absorption (pls see response to Comment #1)

#5. The broader interpretation should better acknowledge remaining uncertainties and regional controls. The analysis covers a short period in January 2023, and IGP fog is also strongly affected by meteorology, land-surface moisture, irrigation, and boundary-layer structure. The manuscript should discuss how these factors may interact with the aerosol-radiation signal, and it should also ensure that the methods section is complete.

Response: This is an important suggestion. Accordingly, text has been added in the Discussion and Conclusions section to acknowledge that the present analysis is based on a single simulation period and that IGP fog is also strongly influenced by regional parameters [Ln 405-416 of revised manuscript].

The interpretations presented in this study, however, are primarily based on model simulations conducted for a single period in January 2023. Winter-time fog over the IGP is a regional phenomenon driven by favourable synoptic-scale influences such as western disturbances (Smith et al., 2023), land-surface moisture enhancement by irrigation practices (Smith et al., 2024), and competing influences from urban surfaces and urban aerosols (Anurose et al., 2024). These factors do not operate independently of the different ARI responses examined in the present study. All these factors can modify radiative cooling, surface energy balance, humidity, turbulence, and boundary-layer depth, thereby influencing overall fog lifecycle. Further, fog conditions significantly impact the applicability or reliability of both satellite aerosol retrievals and in-situ observations at several sites within the study region. This has restricted direct point-to-point validation in this study and highlights the importance of expanding and strengthening the observational network for more robust assessments. Nonetheless, the findings of the present study underscore the necessity of accurately representing the ARI processes in NWP models to improve fog forecasts. Additionally, further studies on aerosol size distribution and chemical composition are essential to enhance the representation of ARI in modelling systems.