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

 # Reviewer 1

General Remarks

This manuscript uses a series of sensitivity tests, conducted in a regional NWP model, to disentangle the relevant impacts of aerosol absorption, scattering, and indirect effects on fog formation and characteristics. The experiment is well-posed and the analysis is generally robust. However, the manuscript is incomplete. Section 2.2 is unfinished. Numerous citations are missing from reference list and some do not appear to exist at all; I find the implications of the latter deeply concerning. Finally, this draft does not engage sufficiently with the existing literature on aerosol-fog interactions. I thus recommend resubmission after major revisions, at which point I would be willing to review the manuscript again.

General Response: We thank the reviewer for the careful assessment of the manuscript and insightful remarks and suggestions. We have revised the manuscript to address the concerns raised.
Regarding the incomplete Section 2.2, we apologise for this oversight. The section has now been completed in the revised manuscript. We have also carefully checked the citations and reference list; all references cited in the manuscript are now included in the reference list, and entries that were incorrect or unverifiable have been corrected or removed.
We understand that the original manuscript did not adequately situate the study within the broader body of relevant work. In response to this, the revised manuscript includes an expanded discussion of prior studies on aerosol-radiation interactions in the context of fog, and how our findings compare with or diverge from existing results. Relevant literature has been incorporated into both the Introduction and the Discussion.
We hope that the revised manuscript addresses the reviewer's concerns fully, and we appreciate the reviewer's willingness to reconsider the manuscript upon resubmission.

Major Comments

#1. L59: "While the role of ACI in fog microphysics has been relatively well studied…" Can you provide a brief (~1 sentence) overview of the consensus here? Presumably this is the same as any other aerosol-cloud interaction, but it would be good to specify.

Response: We agree that the role of ACI in fog microphysics should be briefly clarified. Mainly, studies have suggested that ACI exerts a positive influence on fog lifecycle. The relevant text has been modified as [Ln 59-62 of revised manuscript]

While several previous studies have investigated aerosol impacts on fog, most have primarily focused on ACI, which are generally considered the dominant during fog microphysics and evolution. Several studies have reported 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).

#2. L61-66: You highlight other studies that have looked at the impact of absorbing aerosols on fog. What are the remaining knowledge gaps? How does your study differ from theirs?

Response: With growing evidence of the role of absorbing aerosols in fog, more evaluation is required to understand how important aerosol absorption is in the IGP region in comparison to aerosol scattering. In the present study, we have attempted to examine this. In light of this, the relevant text has been modified as below [Ln 58-87]

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. While several previous studies have investigated aerosol impacts on fog, most have primarily focused on ACI, which are generally considered the dominant during fog microphysics and evolution. 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. Therefore, the ARI effect, particularly its absorbing component, cannot be neglected over the IGP. 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). The influence of absorbing aerosols on fog, the relative contributions of aerosol absorption and scattering to fog evolution have not been examined in modeling studies over the IGP. Hence, it is important not only to study the role of ARI in the fog lifecycle but also to examine the relative contributions of aerosol absorption and scattering in a polluted region like the IGP to fog responses.

*With this background, t*he 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. L89: Section 2.2 is incomplete.

Response: The beginning of Section 2.2 is revised as follows: [Ln 105-111 of the revised manuscript]

Fog over the IGP is most prominent during December-January, with persistent widespread episodes typically beginning in mid-December and extending into January (Singh & Gautam, 2022; Deshpande et al., 2023; Ghude et al., 2023). In the present study, simulations were carried out for the period of 1-10 January 2023, which experienced frequent occurrences of shallow to dense fog events almost daily (IMD, 2023). The DM-Chem model was run for a forecast length of 48 hours based on 0000 UTC initial conditions for each day. Subsequently, forecast outputs from T + 12 to T + 35 hours were considered for analysis from each simulation. A series of experiments was designed to primarily investigate the impact of ARI on fog formation and evolution.

#4. L95: Can you clarify the AI experiment? By how much do you reduce the emissions of aerosols and aerosol precursors in order to obtain PM2.5 < 5ug/m2? How did you determine the necessary emission reductions?

Response: The emissions were reduced by a fraction of 10^3. This has now been clarified in the revised manuscript as follows [Ln 112 -116 of revised manuscript]

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, H_2O_2, DMS, SO_2, DMSO, monoterpene, sea salt) were reduced by a factor of 10^3 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.

#5. L132: I'm not sure I agree that the model compares particularly well with observed LWP. The observed distribution is spatially heterogeneous with a number of moderately-high-LWP regions. In contrast, the model shows quite low LWP everywhere except for a single plume over NW Haryana which contains LWP values substantially higher than are seen anywhere in the observed domain. Although the spatially-averaged LWP is probably similar, I suspect that the dynamics are fairly different.

Response: We agree that the spatial heterogeneity in LWP is not reproduced well by the model when compared with MODIS in terms of intensity or magnitude; therefore, the phrase 'compares well' in Ln132 of the original manuscript warrants revision. We can deduce from Fig. A1 that the spatial coverage of fog is similar, which is itself a challenge in NWP models for fog. Further, it can be noted from Fig 1 (b) that the model has a tendency for earlier dissipation of fog than observed, in terms of visibility. MODIS-based fog/LWP retrieval is largely restricted to daytime (~ 0930-1100 IST). Hence, model LWP values are lower than MODIS-derived values. Nonetheless, Fig A1 provides a qualitative corroboration of the model's performance for fog. The relevant line has now been modified as {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.

#6. Fig 1: I am having difficulty reconciling the contents of the table (1a), which shows the model simulating dense fog every day except one, with the figure (1b) where the model never reaches below "moderate fog." It looks like the shaded envelope (is that the min-max range across time?) maybe dips into dense fog once, but the line (median?) certainly does not. Please also expand the caption to describe the meaning of the lines vs shaded envelopes. It may also be helpful to indicate your study period (0530-0830 IST) on Fig 1b.

Response: We thank the reviewer for pointing out this ambiguity. We agree that the original caption did not sufficiently distinguish the two panels, which may have led to the apparent inconsistency between Fig. 1a and Fig. 1b. Fig. 1a is intended to assess fog-event detection and is based on the minimum visibility during the early-morning fog window, rather than on strict hour-to-hour correspondence. Therefore, a day may be classified as dense fog in Fig. 1a if the model simulates dense-fog visibility at any time within the selected window. In contrast, Fig. 1b shows the mean diurnal evolution of visibility over 1–10 January 2023, with the line representing the mean hourly visibility and the shaded envelope representing the ± 1 standard error across days. As a result, short-lived dense-fog conditions on individual days may appear

in Fig. 1a but may not be reflected in the central line in Fig. 1b after averaging across the full study period. The shaded envelope in Fig. 1(b) does extend into the dense fog category, which is consistent with this explanation. We have revised the caption to clearly describe the meaning of the lines and shaded envelopes. Further, in the text (Ln 153-154) we have mentioned that *Subsequent analyses in this study emphasise dense fog-affected hours from 00 UTC to 03 UTC (0530 – 0830 IST), during which the model has shown reliable performance*.

(a)

Fog Condition at Minimum Visibility		
Date	**Observed**	**DM-Chem1.0**
01-Jan-23	Dense Fog	Moderate Fog
02-Jan-23	Dense Fog	Dense Fog
03-Jan-23	Moderate Fog	Dense Fog
04-Jan-23	Dense Fog	Dense Fog
05-Jan-23	Dense Fog	Dense Fog
06-Jan-23	Dense Fog	Dense Fog
07-Jan-23	Dense Fog	Dense Fog
08-Jan-23	Dense Fog	Dense Fog
09-Jan-23	Dense Fog	Dense Fog
10-Jan-23	Dense Fog	Dense Fog

(b)

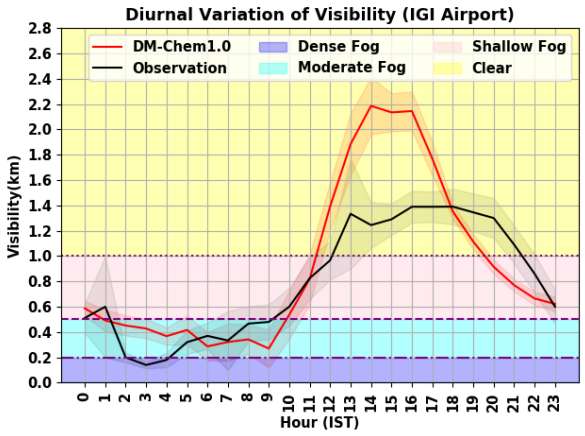


Figure 1: Comparison of observed and simulated visibility at IGI Airport for 1-10 Jan 2023 in terms of (a) daily minimum visibility within the 0300–0800 IST window, and (b) mean diurnal variation of visibility averaged over the 10-day study period, where solid lines denote the 10-day hourly mean for observations (black) and model (red), and shaded envelopes represent ±1 standard error across the days at each hour.

#7. Figs 2-3 / L144 and L150: why does your definition of fog-affected change from LWP>0 to q1>0.01 g/kg?

Response: In section 3.3.1, we assess the impact of all experiments on the formation and evolution of fog formation and evolution. Both LWP > 0 and near-surface ql > 0.01 g/kg are widely used criteria for indicating the presence of fog. However, the LWP criterion is subject to some variability: some studies recommend a minimum non-zero threshold for LWP rather than LWP > 0 (e.g., Toledo et al., 2021, ACP, doi:10.5194/acp-21-13099-2021), and the integration depth used to compute LWP also varies across studies. Hence, in addition to LWP, we also assess fog using near-surface ql (along with visibility conditions) so that the robustness of results can be ensured. Later, in section 3.4, we use ql only to examine fog at different vertical levels.

#8. Fig 5: It will be more clear when the grey shading is applied to all panels (see minor comments) but there are differences in the temporal evolution of the 4 quantities plotted. Can you comment on the relative behaviour of these quantities, e.g. the fact that LWR anomalies grow

smoothly from 2200-1000 but the T and RH anomalies begin sharply at 0700, the difference in temporal evolution of T anomalies amongst the different experiments, and the complex behavior of the BLH anomalies? For BLH, please comment in particular on the change in sign of the ARII-A anomaly at ~1400?

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#26. Fig 5: I would recommend the following: (i) shade the hours without fog (1400-2100) instead of the hours with; (ii) include this shading on all panels; and (iii) expand the caption to explain the meaning of the shaded regions. This will make both the figure and its explanation in L193-196 easier to interpret.

Response (8 & 26): As per the reviewer's suggestion, Figure 7 (Figure 5 in the original draft) has been revised to include shading for non-fog hours. Additionally, approximate times of sunrise and sunset are also indicated on the plots. Section 3.3.2 has been revised to include some discussion on the evolution of the parameters, as presented below [Ln 246-300 of the revised manuscript].

3.3.2 Change in near-surface radiation fluxes and temperature

Figure 7 presents the mean diurnal variations in the differences of net longwave radiation (Fig. 7a), near-surface temperature (Fig. 7b), relative humidity (Fig. 7c), and boundary layer height (BLH) (Fig. 7d) across different experiments, each compared to the Control experiment. As shown in Figure 5, the late afternoon to early evening period is largely fog-free across the model domain in all experiments. Since Figure 7 is based on spatially averaged values over the entire domain, the 1430-1900 IST period is shaded in yellow to denote the hours when fog is absent in all experiments across the domain.

Among the surface radiation components, net longwave radiation dominates during winter, especially in January, when dense fog events commonly occur over the IGP, including the study region. Hence, as fog coverage starts to decline from 1400 hours onwards, the differences in LWR among the various experiments also decrease, with minimal differences from 1800-2100 hours, reflecting a reduced role of fog and aerosol processes. At other, fog-prone hours, however, notable differences emerge. In the ARII-A experiment, an increase in downward LWR at the surface is observed. This can be attributed to the enhanced fog in this experiment, which contains more water droplets that absorb and re-emit longwave radiation, thereby increasing net downward LWR. A schematic for the radiation processes in the different processes is displayed in Fig. 8. Under normal conditions, absorbing aerosols absorb incoming shortwave radiation, reducing the amount reaching the surface and causing ambient warming. This leads to atmospheric warming at the aerosol layer, while the surface may experience reduced shortwave heating. This warming limits the vertical growth at the time of fog formation and evolution. Hence, in the absence of aerosol absorption, the fog is denser and higher. Due to the presence of denser fog, which is highly effective at emitting downward longwave radiation (Li et al, 2021), an increase

in net longwave radiation at the surface is exhibited in the ARII-A compared to the Control experiment.

In contrast, in the ARII-S experiment, fog is suppressed. Scattering aerosols reflect and scatter solar SWR back to space, leading to even stronger reductions in surface heating compared to absorbing aerosols. Therefore, in the ARII-S experiment, where scattering is absent, more solar radiation reaches the surface, causing stronger surface warming and, consequently, a greater increase in upwelling (outgoing) longwave radiation than in the ARII-A case. The reduced fog presence limits the re-emission of longwave radiation back to the surface, resulting in a decrease in net LWR compared to Control. In the AI experiment, where aerosols are entirely absent, the surface experiences strong direct heating due to uninhibited solar radiation. This leads to significantly enhanced outgoing longwave radiation, while downward LWR is minimal due to the lack of aerosols and fog. Consequently, the net LWR at the surface is substantially reduced.

The presence of enhanced fog in the ARII-A experiment leads to a decrease in near-surface temperature (Fig. 7b) and consequently an increase in relative humidity (Fig. 7c). The opposite effect is seen in the ARII-S experiment, where reduced scattering leads to increased near-surface temperature and reduced RH relative to the Control experiment. Notably, near-surface temperature, and consequently relative humidity, respond more directly to sunrise and sunset than net longwave radiation, which is indirectly modulated by changes in temperature, RH and fog. The sunrise-sunset transitions control the onset and cessation of shortwave (SW) radiative heating. As evening approaches, the shortwave pathway of aerosol-radiation interactions weakens and eventually becomes inactive, leading to a gradual reduction in temperature and relative humidity differences among the experiments. In the AI experiment, the virtual absence of aerosols and fog allows for greatly enhanced surface warming due to more incoming SW radiation. Consequently, most increase is observed in temperature (Fig. 7b), while relative humidity (RH) decreases (Fig. 7c). Even in non-fog hours, there is a difference of about 0.5°C between the Control and AI experiments.

Boundary layer height (Fig 7d) is closely linked to daytime temperature evolution. During nighttime and fog hours, BLH is higher in the ARII-A experiment. Normally, absorbing aerosols strengthen the inversion cap by stabilising the boundary layer and enhancing radiative cooling, which suppresses BLH development (Bharali et al., 2024; Su et al., 2020). In their absence, the inversion weakens, allowing BLH to increase. In contrast, scattering aerosols reduce radiative cooling at night. Their absence in the ARII-S experiment slightly decreases this suppression, leading to a modest increase in BLH. However, it is worth noting that aerosol scattering impacts longwave radiation to a lesser extent than shortwave, unless under conditions of heavy particulate pollution (Liu et al., 2024). As fog dissipates during late morning and solar radiation intensifies into afternoon hours, the BLH response changes. The elevated atmospheric heating fuels growth in BL in the Control experiment. This absorption driven heating is absent in ARII-A experiment and while surface heating is enhanced in ARII-S experiment. Consequently, the BLH difference turns negative from around 1100 hours in ARII-A and positive in ARII-S. As we approach post-maxima afternoon hours (which are also fog free hours), there is a changing balance between weakened atmospheric heating and greater near-surface heating driven turbulence in the ARII-A experiment. The decline in BLH after reaching daytime maxima is more gradual in the

ARII-A experiment which leads to a sharp rise in the BLH difference between ARII-A and Control during this window (1400-1500 hours).

Option 1

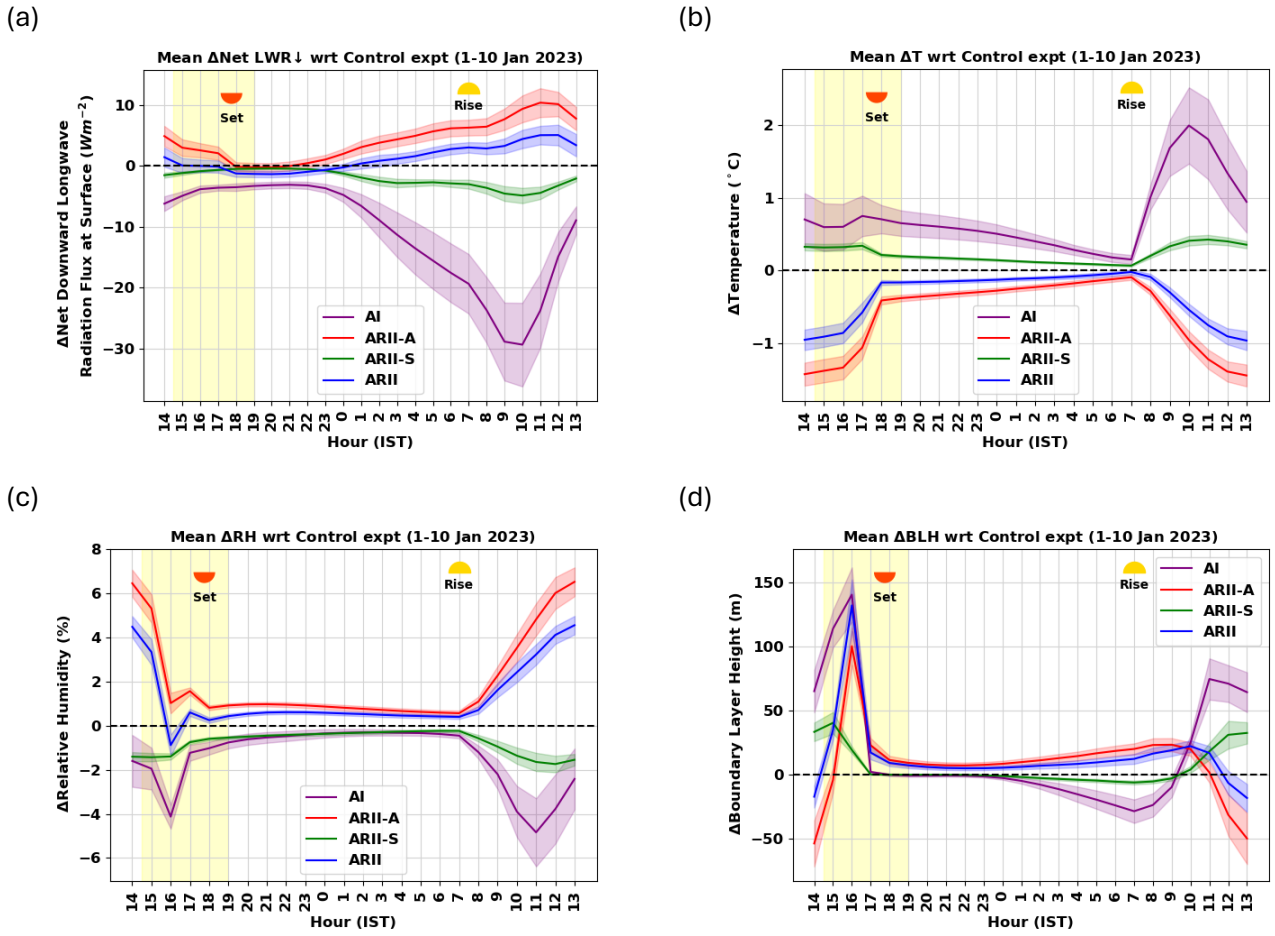


Figure 7: Diurnal variability of changes with respect to the *Control* experiment [Experiment-Control] (along with standard error) for (a) Net Surface Longwave Radiation, (b) near surface temperature, (c) relative humidity, and (d) boundary layer height. The yellow shading indicates hours during which fog is absent in all experiments across the model domain. Approximate sunrise and sunset times during the study period are also marked in each panel.

Option 2

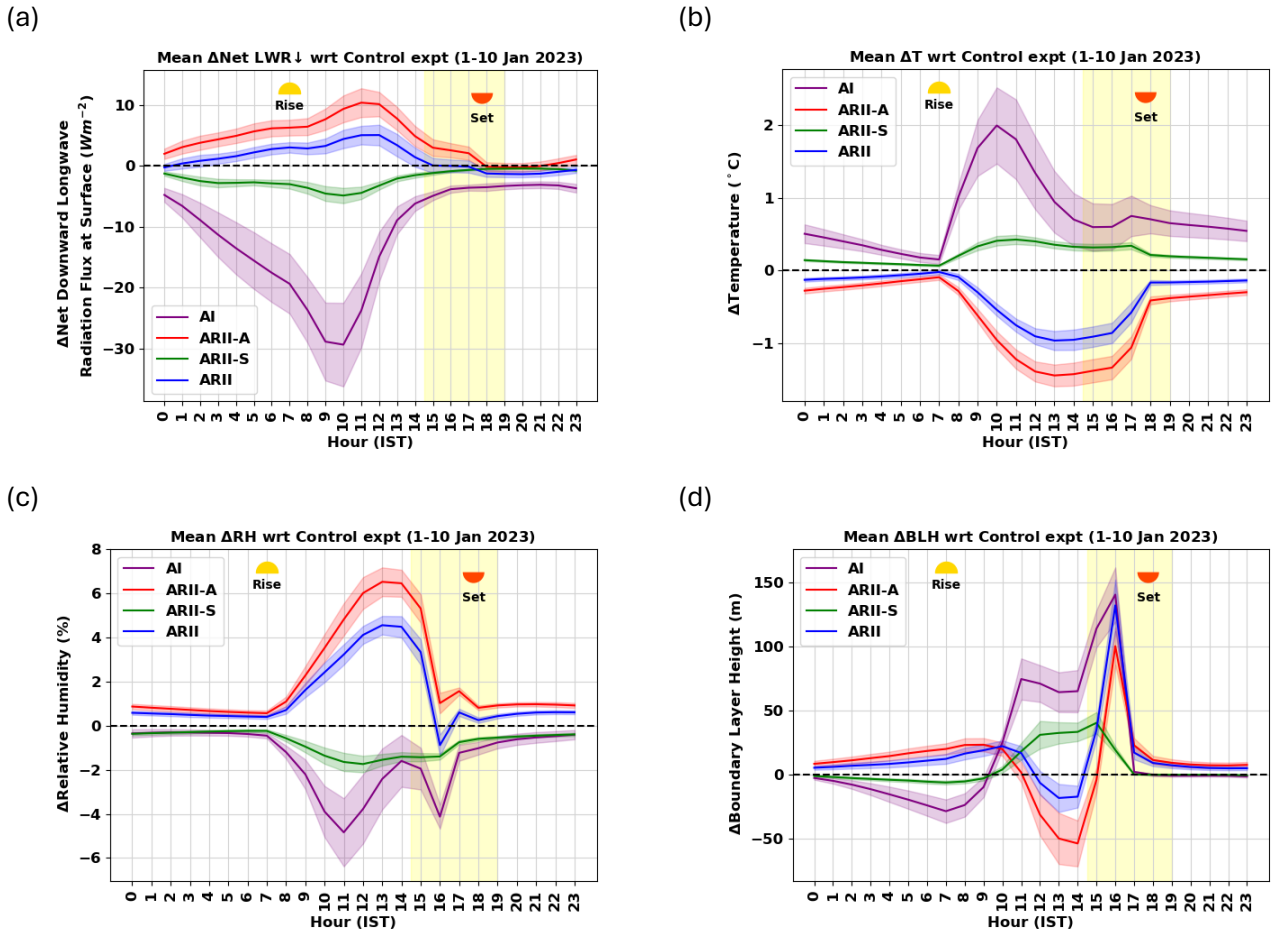


Figure 7: Diurnal variability of changes with respect to the *Control* experiment [Experiment-Control] (along with standard error) for (a) Net Surface Longwave Radiation, (b) near surface temperature, (c) relative humidity, and (d) boundary layer height. The yellow shading indicates hours during which fog is absent in all experiments across the model domain. Approximate sunrise and sunset times during the study period are also marked in each panel.

#9. L255-256: "Notably, in the *AI* experiment (Fig. 7e), fog does not form at all…" It clearly does form, see also Fig. 3. Part of why it appears lower in Fig 7e is that you changed the colour scale in panel e compared to the others; this does not appear to be necessary and leads to confusion, so I recommend using the same colour scale in all panels.

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 # 32. Fig 7: Please use the same colour scale for all panels. The ranges are close enough that I do not see a strong reason for using a different scale for panel e. Please also clarify whether these are heights above the surface in each gridcell or relative to some common reference.

<u>Response (9 & 32)</u>: Fig. 5 (Fig. 3 in original draft) shows the percentage of domain area affected by fog according to the criterion $q_l > 0.01$ g/kg, which peaks at only 15% for the *AI* experiment

at 0700 hours (IST). However, in Fig. 9 (Fig. 7 in original draft), we consider the spatially averaged q_l over the entire domain to study its vertical profile. At the domain-averaged scale, the criterion of $q_l > 0.01$ g/kg is never satisfied in the *AI* experiment. The color scale of Fig 9(a-d) is in units of g/kg while that for Fig 9e is in units of 10^{-2}g/kg. Hence, Fig 9(e) would have appeared blank if a similar scale had been used for all sub-plots. However, following the reviewer's viewpoint that this might lead to confusion, the text is modified as follows [Ln 322-323 of revised manuscript]:

In the AI experiment (Fig. 9e), fog does not form at all, with q_l values remaining below the minimum fog threshold of 0.01 g kg^{-1} at the domain-wide average level. Thus, Fig 9e is shown with a different q_l scale.

#10. Section 3.4: Would this section be better placed with the model evaluation than with the results? The fact that absorbing aerosol is present in observations, as well as in your model, provides evidence that your experimental setup is reasonable but does not directly corroborate your results which are entirely simulated.

Response: We agree with the reviewer's viewpoint. Section 3.4 is moved to Section 3.2 in the revised manuscript following model validation in Section 3.1. Further, instead of indicating that the presence of absorbing aerosols corroborates our model results, we discuss 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.

#11. L327: "primarily via aerosol-radiation interactions" This is incorrect, your results indicate that ARI is important but that ACI dominates (relative magnitude of anomalies in ARII vs AI)

Response: We agree with the reviewer's remark. The focus of this study is the influence of ARI on fog in the IGP. While we don't directly evaluate the role of ACI in the present study, the *AI* (no/low aerosol) experiment serves as its proxy to indicate that fog formation is dominated by ACI. Nonetheless, our study shows that ARI plays a non-trivial role in the growth and dissipation of fog. In light of this, the relevant text is modified in the revised manuscript as follows [Ln 365-370 of revised manuscript]:

Widespread dense fog is a frequent and persistent phenomenon during the winter season over the Indo-Gangetic Plains. This region is also characterised by high aerosol loading, and several studies have reported appreciable concentrations of absorbing aerosols in the region. This makes it important to examine how aerosol-radiation interactions can influence the formation, persistence and dissipation of fog in the region. In this study, four targeted numerical experiments were conducted using the DM-Chem1.0 model to isolate the relative contributions of the absorbing and scattering components of ARI to fog characteristics in the IGP region during January 2023.

#12. L346-347: The presence of absorbing aerosol in observations does not directly demonstrate that those aerosols influence fog.

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#13. Discussion is missing any comparison with previous studies. Please elaborate on how your results compare with others who have investigated the impacts of ARI on fog.

Response (12 & 13): The following text has been added/edited in the revised manuscript to include comparisons with some earlier studies [Ln 384-404 of the revised manucsript]

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.

Minor Comments

#14. L29: Zhou et al. (2019) is not included in the reference list; is this the best reference for aerosol-radiation interactions?

Response: The reference has been updated to that of [Ln 27-28 of revised manuscript]

Aerosols can directly scatter or absorb solar radiation, and together these processes constitute aerosol–radiation interactions (IPCC, 2013).

Intergovernmental Panel on Climate Change (IPCC) (2013). Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

#15. L35: Sarkar and Panda (2024) is not included in the reference list, and the only Sarkar and Panda (2024) I can find online discusses chromatography for biotechnology.

Response: The reference has now been included in the references list in the revised manuscript:

Sarkar, A. and Panda, J.: Significance of anthropogenic black carbon in modulating atmospheric and cloud properties through aerosol-radiation interaction during a winter-time fog-haze, Atmospheric Environment, 334, 120720, https://doi.org/10.1016/j.atmosenv.2024.120720, 2024.

#16. L48: I believe IGI is the airport and you want IGP here?

Response: Yes, this was an oversight. The relevant line has been corrected in the revised manuscript [Ln 46]:

Geographically, the IGP spans from 73°E, 32°N to 89°E, 21°N, encompassing diverse agro-climatic regions (Ali and Kumar, 2016).

#17. L63-64: "ARI-induced aerosol absorption" should be corrected

Response: The sentence has been modified as [Ln 68-70]

.....while Anurose et al. (2024) reported similar fog-clearing patterns over rural areas attributed to radiative heating by absorbing aerosols through ARI.

#18. L64: "both emissions and ARI significantly modulate fog processes" what do you mean by emissions here? Also, in the context of this paragraph, be careful not to conflate "ARI" and "absorption."

Response: The line has been revised as follows [Ln 70-72 in revised manuscript]

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.

#19. L88: These citations are not included in the reference list.

Response: These references have been updated to include studies that have carried out long-term assessments of fog over IGP. The relevant sentence has been modified as [Ln 105-107 of the revised manuscript]

Fog over the IGP is most prominent during December-January, with persistent widespread episodes typically beginning in mid-December and extending into January (Singh et al., 2022; Deshpande et al., 2023; Ghude et al., 2023).

#20. L109: cite MODIS data product.

Response: Citation has been added [Ln 131-133]

Liquid water path (LWP) and single scattering albedo (SSA) were derived from the data products of the MODIS-Terra satellite. LWP was obtained from the MOD06_L2 cloud product (Platnick et al., 2015), while SSA is available as a standard retrieval within the MOD04_L2 aerosol product, where it is estimated using the Deep Blue algorithm (Levy et al., 2015).

- *Levy, R., Hsu, C., et al., 2015. MODIS Atmosphere L2 Aerosol Product. NASA MODIS Adaptive Processing System, Goddard Space Flight Center, USA: http://dx.doi.org/10.5067/MODIS/MOD04_L2.006*
- *Platnick, S., Ackerman, S., King, M., et al., 2015. MODIS Atmosphere L2 Cloud Product (06_L2). NASA MODIS Adaptive Processing System, Goddard Space Flight Center, USA: http://dx.doi.org/10.5067/MODIS/MOD06_L2.006*

#21. L148-149: Although the decision to plot the diurnal variation from 1800 one day to 1700 the next makes sense when cross-referencing Figs 1 and 3, it would be helpful to mention in the text that you are doing this to centre the period with lowest visibility / highest fog.

Response: Following the reviewer's suggestion, the following line has been added in the text to clarify the reason behind the order of hours in x axis of the plot [Ln 201-203 of the revised manuscript]:

The diurnal cycle is plotted from the evening hours of one day to the late afternoon of the following day so that the nighttime-to-morning period, during which visibility is generally lowest, and fog occurrence is highest, remains centred and continuous in the analysis.

#22. L150: this citation is not included in the reference list.

Response: The citation has now been added to the reference list

- *Maronga, B. and Bosveld, F. C.: Key parameters for the life cycle of nocturnal radiation fog: a comprehensive large-eddy simulation study, Quart J Royal Meteoro Soc, 143, 2463–2480, https://doi.org/10.1002/qj.3100, 2017.*

#23. L156-157: these citations are not included in the reference list.

Response: The citations have now been added to the reference list

- *Boutle, I., Price, J., Kudzotsa, I., Kokkola, H., and Romakkaniemi, S.: Aerosol–fog interaction and the transition to well-mixed radiation fog, Atmospheric Chemistry and Physics, 18, 7827–7840, https://doi.org/10.5194/acp-18-7827-2018, 2018.*
- *Wagh, S., Kulkarni, R., Lonkar, P., Parde, A. N., Dhangar, N. G., Govardhan, G., Sajjan, V., Debnath, S., Gultepe, I., Rajeevan, M., and Ghude, S. D.: Development of visibility equation based on fog microphysical observations and its verification using the WRF model, Model. Earth Syst. Environ., 9, 195–211, https://doi.org/10.1007/s40808-022-01492-6, 2023.*

#24. L161: "48% increase in fog extent by around 48%"

Response: Yes, this is an oversight. The sentence has been corrected as [Ln 216-216]

Error! Reference source not found. (left panel) shows an increase in fog extent by around 48 %, …

#25. Fig 4: Caption might be more clear as "Spatial distribution of the mean difference in fog liquid water path…" Also, perhaps it is just my screen but I find this colourscale challenging to interpret. It looks like the negative values go green – blue – darker green – darker blue, but my eye wants to read greens first and then blues, making the figure unintuitive. Would it be easy to modify?

Response: As per Reviewer's suggestion, the colour scale in Fig.6 (Fig 4 in the original manuscript) has been revised to group all shades of blues and green, so now the progression goes from dark blue → blue → dark green → green. We hope this facilitates figure interpretation. Caption for Fig. 6 has also been edited as below, following the reviewer's suggestion

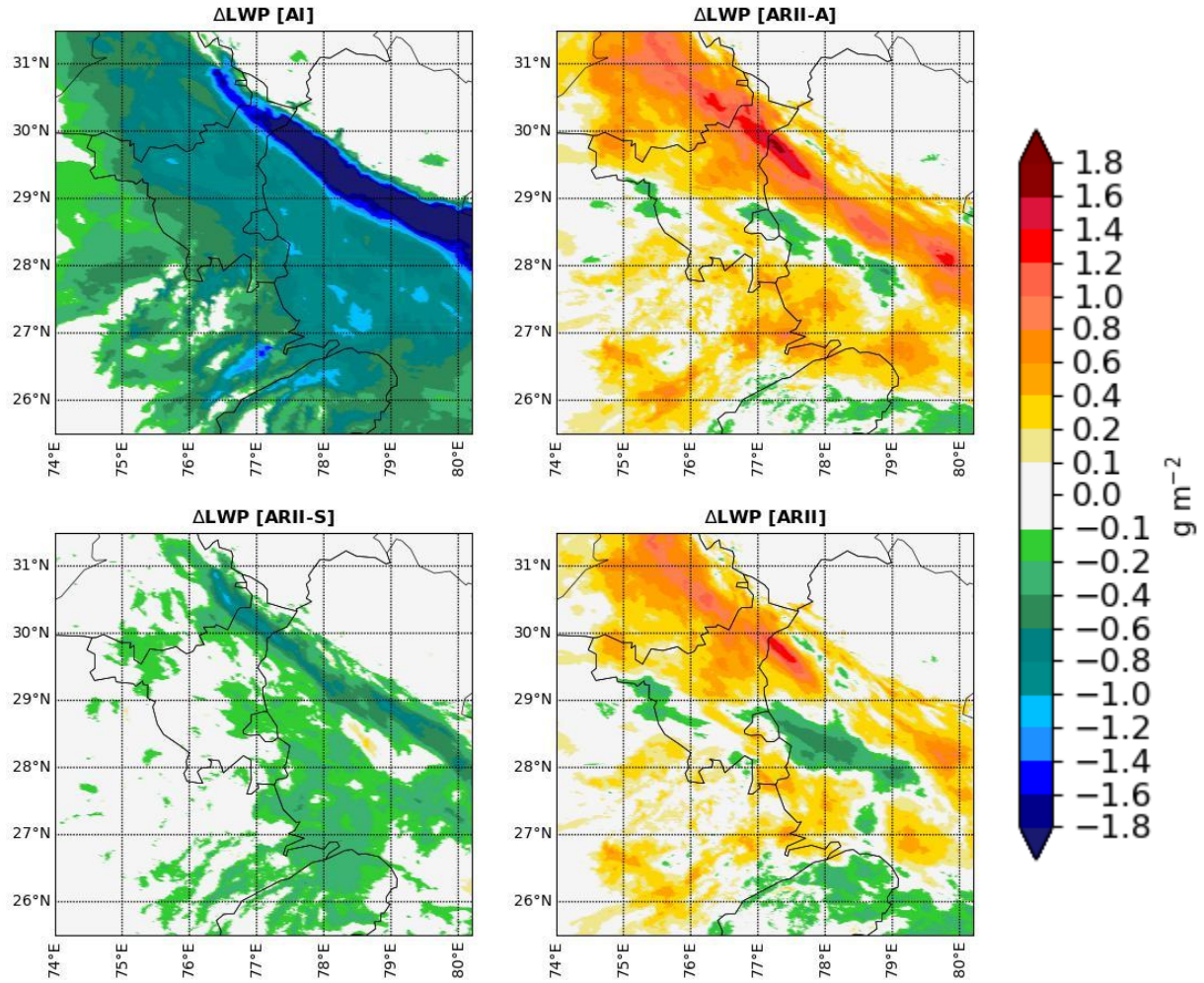


Figure 6: Spatial distribution of the mean difference in fog liquid water path (LWP gm^{-2}) [Expt-Control] for 00-02 UTC (0530 - 0730 IST)

#26. Fig 5: I would recommend the following: (i) shade the hours without fog (1400-2100) instead of the hours with; (ii) include this shading on all panels; and (iii) expand the caption to explain the meaning of the shaded regions. This will make both the figure and its explanation in L193-196 easier to interpret.

Response: Please see the response to comment #8 above.

#27. L220: *The* presence of enhanced fog…

Response: Revised. [Ln 275 of revised manuscript]

#28. Fig 6: Please improve the kerning in the orange boxes to make it easier to read. Also please clarify in the description of the control experiment where the absorbing aerosols cause warming (elevated, not surface).

Response: Spacing has been improved in the orange boxes in Fig. 8 (Fig 6 in the original manuscript). Please find the revised figure below, which should be easier to read. It has now been clarified in the text that [Ln 259-261 of the revised manuscript]

Under normal conditions, absorbing aerosols absorb incoming shortwave radiation, reducing the amount reaching the surface and causing ambient warming. This leads to atmospheric warming at the aerosol layer, while the surface may experience reduced shortwave heating. This warming limits the vertical growth at the time of fog formation and evolution.

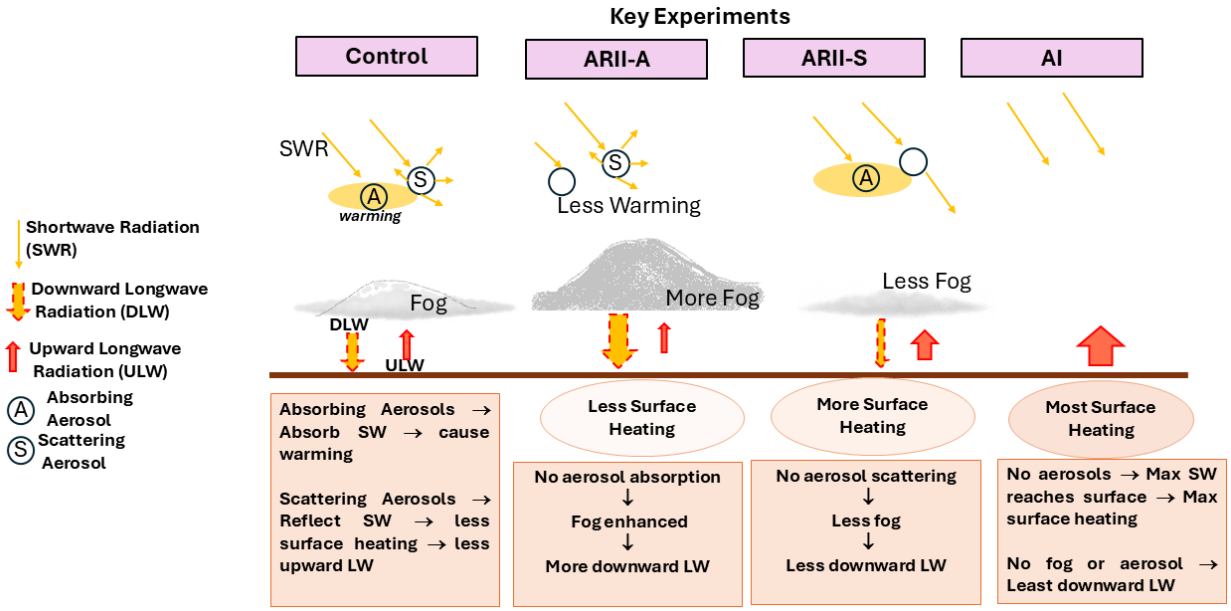


Figure 8: Schematic for key radiative processes in different experiments

#29. L261: as L48, should this read IGP not IGI? Also it should be "over *the*"

Response: Revised. [Ln 328 of revised manuscript]

This suggests that the absence of aerosol absorption can reduce fog height by over 20%, emphasising the non-negligible contribution of ARI in combination with the dominant role of ACI over the IGP during dense fog events.

#30. L264-265: The fact that regions with surface altitudes >450m were excluded from your analysis was not previously mentioned. Please do so and elaborate on the reasoning for this decision.

Response: While NWP models are operational over mountainous/hilly regions worldwide, these regions continue to pose a challenge because terrain modifies airflow at very fine spatial scales. This becomes more important in the case of fog because turbulence and radiation are difficult to parameterise in complex terrains (Pu et al, 2016; Li et al, 2024). Further, aerosol interactions at higher altitudes can be much more complex than on flatter terrain because the same aerosol radiative effect is coupled to a very different boundary-layer and terrain-flow environment. Since the present study is a sensitivity analysis to absorbing and scattering components of ARI in relation to fog, we have excluded regions with high surface altitudes while doing any domain-wide analysis. This masking avoids mixing fog responses over relatively flat terrain with those over complex terrain, where the controlling mechanisms may differ. The excluded regions mainly correspond to the Himalayan foothill/hilly areas in the north-eastern part of the domain and the Aravalli hills in the south-western part. The 450 m threshold was selected after examining the distribution of surface altitude over the model domain, so as to retain the plains-dominated region while excluding elevated terrain that could introduce additional terrain-related complexity.

[ref: Pu, Z., Chachere, C. N., Hoch, S. W., Pardyjak, E., and Gultepe, I.: Numerical Prediction of Cold Season Fog Events over Complex Terrain: the Performance of the WRF Model During MATERHORN-Fog and Early Evaluation, Pure Appl. Geophys., 173, 3165–3186, https://doi.org/10.1007/s00024-016-1375-z, 2016.

Li, X. and Pu, Z.: Effects of surface moisture flux on the formation and evolution of cold fog over complex terrain with large-eddy simulation, Quart J Royal Meteoro Soc, 150, 3013–3027, https://doi.org/10.1002/qj.4748, 2024.]

As per the reviewer's suggestion, the exclusion of regions with >450m surface altitude is now mentioned in section 2.2 of the revised manuscript. Please find the associated text in Ln 120-122 of the revised manuscript.

The simulations were carried out for the outer domain of the DM-Chem1.0 setup (Table 1), which includes most of the IGP region. Some elevated regions within the domain (with surface altitudes above 450m) were excluded from domain-wide analyses to minimise the influence of terrain-controlled fog processes.

#31. L272: "In certain regions, ..." It would be better to specify that of the two regions you isolated for further analysis, the one with a negative fog height response to ARII-A had its BC concentrated near the surface.

Response: The sentence has been modified following the reviewer's suggestion [Ln 340-314 of revised manuscript]:

In the region exhibiting a negative fog height response to the ARII-A experiment, there is a higher concentration of absorbing aerosols (BC) near the surface, while concentrations above BLH are nearly an order of magnitude lower.

#32. Fig 7: Please use the same colour scale for all panels. The ranges are close enough that I do not see a strong reason for using a different scale for panel e. Please also clarify whether these are heights above the surface in each gridcell or relative to some common reference.
Response: Please see the response to comment **#9** earlier in this document.

#33. Fig 8: The text said 03 UTC / 0830 IST, but the caption says 00 UTC / 0530 IST.
Response: Yes, we thank the reviewer for pointing out the oversight. The caption of Fig 10 (Fig. 8 in the original manuscript) has accordingly been revised:
Figure 10: Difference in Fog Height with respect to the Control experiment at 03 UTC (0830 IST)

#34. Fig 9: It would be more typical for this colour scale to be reversed, with positive values in green/yellow.
Response: As per the reviewer's suggestion, the colour scale for Fig 2 (Figure 9 in the original manuscript) has been modified as below

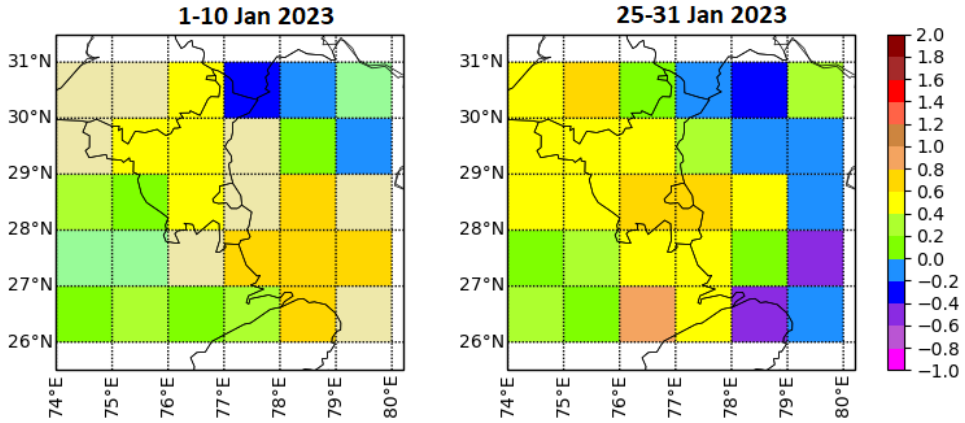


Figure 2: Mean Absorbing Aerosol Index in the Domain. Left:1-10 Jan 2023, Right: 25-31 Jan 2023 (Clear days)
Source: GOME-2 / MetOp-C absorbing aerosol index

#35. L326: "fog formation persistence" should this be formation *and* persistence?
Response: The text has been revised as follows [Ln 365-368 of revised manuscript]:

Widespread dense fog is a frequent and persistent phenomenon during the winter season over the Indo-Gangetic Plains. This region is also characterised by high aerosol loading, and several studies have reported appreciable concentrations of absorbing

aerosols in the region. This makes it important to examine how aerosol-radiation interactions can influence the formation, persistence and dissipation of fog in the region.

#36. L331: replace "spatially" with "horizontally"

Response: The line has been modified as [Ln 371-372 of the revised manuscript]

When the absorbing effects of aerosols were suppressed in the ARII-A experiment, fog was found to be denser and more persistent, covering a larger horizontal area and extending through a greater vertical depth.

#37. L335: remove "furthermore"

Response: Revised. [Ln 376 of revised manuscript]

#38. L340-341: "though not necessarily of dense character" is this phrase misplaced?

Response: We agree that the phrase seems awkwardly placed and detracts from the sentence's clarity. It has accordingly been modified as [Ln 380-381 of the revised manuscript]:

It shows the lowest fog coverage, with fog mostly confined to nighttime hours, followed by the earliest and most rapid dissipation.

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 PM2.5 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, H_2O_2, DMS, SO_2, DMSO, monoterpene, sea salt), were reduced by a factor of 10^3 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.