Response to Referee #1

The paper "Spatial-scale dependence of aerosol indirect effects over land in eastern China: A comparative analysis" by Yuqin Liu et al. investigates the effect of spatial scale on the sensitivity of cloud droplet effective radius (CER) to aerosol optical depth (AOD) and on the sensitivity of cloud droplet number (N_d) concentration to AOD, for two different time periods (2008–2014 and 2015–2022) in the eastern region of China. The present study is of scientific interest, falls within the scope of ACP, the manuscript is really well-written and even better well-structured, the presentation clear, the language fluent. I recommend publication in ACP; however, I recommend to the authors the following revisions and modifications. Since the study is already at a good level, I would argue the authors to see the comments in a positive way as made, raised by an approach and a view point of an external reader, as modifications that would improve the flow, and help other readers to better understand the outcomes and the scope of the study, improving also specific points that it seems that there are gaps to fill.

The authors are grateful to Referee #1 for the valuable time spent on thorough reading our manuscript and providing expert views to guide us for improving the manuscript with the main and specific points and the references. We have taken notice of all comments, listed below in black, and made many changes to the manuscript to address these, together with the comments from the other referees. All modifications in the revised manuscript have been highlighted for your convenience. We address each of your comments below and refer to our responses in the revised manuscript and provide line numbers (**clean version**) and copy text in "quotes". Finally, relevant references have been added to the reference list.

Main points

1) Abstract: The suggestion here is to re-write it in a different concept. The suggestion is to add somewhere in the beginning a sentence delineating the objective to the study, something like "… aims to reveal the sensitivity patterns of aerosol indirect effects to spatial scales, …" and then referring to the datasets used to facilitate the results and the basic outcomes. In addition, please re-visit the sentence "decreases, reflecting the weaker of aerosol-cloud interactions for declining aerosol concentrations.". It needs to be written clearer.

Answer: Thank you for this constructive comment. The abstract has been fully rewritten following the suggested conceptual framework. A clear statement of the study objective has been added at the beginning of the abstract as recommended. Subsequent content of the abstract is reorganized to sequentially introduce the utilized datasets, analytical methods, key results and main conclusions, to ensure a logical and coherent narrative that closely links data application to outcome derivation.

"This study aims to reveal patterns of the sensitivity of aerosol indirect effects to spatial scales and investigate the regulatory role of the liquid water path (LWP) in aerosol-cloud interactions over land in eastern China. Using MODIS and CALIOP satellite observations, we systematically analyzed the relationships between aerosol optical depth (AOD) and cloud properties (cloud droplet effective radius, CER; cloud droplet number concentration, N_d) during two periods: 2008–2014 (period 1, high AOD) and 2015–2022 (period 2, decreasing AOD). The results show two distinct regimes of CER variation with LWP: a rapid growth regime (LWP < 55/50 g/m²) and a decreasing regime (LWP = 55-135/50-100 g/m²) (thresholds vary by period). The sensitivity of CER to AOD (S_{CER}) exhibited a negative correlation, with stronger sensitivity in the decreasing LWP regime than in the rapid growth regime. Spatial scale (characterized by buffer size and study area) significantly modulated these sensitivities: $|S_{CER}|$ and the positive sensitivity of N_d to AOD (S_{Nd}) both decreased with increasing spatial scale. Optimal buffer sizes range from 6°×6° to 10°×10°: increasing with study area in period 2 but decreasing in period 1 for the decreasing LWP regime. Compared with period 1, $|S_{CER}|$ in period 2 significantly reduced, reflecting the weakened aerosol-cloud interactions due to declining aerosol concentrations. Additionally, the optimal buffer sizes for S_{Nd} are larger in the 8°×8° and 10°×10° study areas than in 4°×4° and 6°×6° areas. This study reveals the scale-dependence of aerosol-cloud interactions, providing critical observational support for optimizing climate model parameterization schemes."

The ambiguous sentence "decreases, reflecting the weaker of aerosol-cloud interactions for declining aerosol concentrations" has been revised for clarity and grammatical accuracy. The revised version is: "Compared with period 1, $|S_{CER}|$ in period 2 significantly reduced, reflecting the weakened aerosol-cloud interactions due to declining aerosol concentrations.", to explicitly clarify the causal relationship and eliminate the grammatical flaw in the original expression.

2) "Buffer size": Though the authors have tried to delineate the concept, it needs further improvements. From the reviewer's point of view, and since this is a core-element of the study, I would suggest further effort on explaining this concept. I would argue the authors to address this as a constructive point, improvement is needed.

Answer: We sincerely appreciate the reviewer's constructive comment on the clarification of "buffer size", which is indeed a core concept of this study. We have further refined and supplemented the explanation of this concept in the revised manuscript to enhance its clarity and comprehensibility. We have also ensured the consistency of the concept's expression throughout the manuscript to avoid any potential ambiguity for readers. See the text in the Section 2.4 lines 331-333 and 338-364.

The text "Here, the spatial scales are described by two parameters: study area size (the geographic scope of the analysis) and buffer size (the local spatial extent around each observation point for aggregating aerosol and cloud data)." in Section 2.4 lines 331-333.

The text "Buffer size refers here to a circular spatial domain centered at each CALIOP-detected point in the study area where CALIOP detected the presence of aerosols. Within this circular domain, MODIS-retrieved cloud and aerosol data (AOD, CER, N_d, LWP) are spatially averaged to construct matched aerosol-cloud datasets at different local scales. This approach assumes that aerosol properties are reasonably homogeneous between adjacent clear and cloudy regions (Anderson et al., 2003; Quaas et al., 2008), which is a plausible considering the short-range transport of aerosols (e.g., 10-300 km) and the near-simultaneous observations (1-2 minutes) by MODIS and CALIOP within the A-Train constellation.

Buffer zones with sizes increasing from 10 to 300 km (10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 70 km, 80 km, 90 km, 100 km, 120 km, 140 km, 150 km, 160 km, 180 km, 200 km, 250 km, and 300 km) were determined within the whole study area by using CALIOP data. Previous observations indicate that the typical horizontal scale of cloud clusters ranges from tens to hundreds of kilometers (Zhang et al., 2024; Cai et al., 2022), supported by CloudSat/CALIPSO satellite data showing power-law distributed cloud scales (10-1000 km fitting range) covering major cloud types (Zhang et al., 2024) and regional evidence of consistent multi-season, multi-latitude cloud extents (Cai et al., 2022). Meanwhile, aerosol spatial homogeneity varies with distance: local-scale aerosols (≤ 50 km) exhibit high homogeneity due to consistent sources and stable diffusion, while regional-scale aerosols (>

100 km) show enhanced heterogeneity from multi-source mixing and atmospheric transport (Hassan et al., 2024; Mohebalhojeh et al., 2026). Thus, the 10–300 km buffer range covers both cloud characteristic scales and the aerosol homogeneity transition range, ensuring that MODIS data averaging effectively captures cloud-aerosol coupling. This range avoids insufficient MODIS pixel coverage due to excessively small buffer sizes (< 10 km). It also prevents conflation between regional meteorological variations and local aci signals arising from overly large buffer sizes (> 300 km), as synoptic-scale circulation and other regional meteorological changes may interfere with local aci signals (Quaas et al., 2010). Meanwhile, this range aligns with the 50–150 km buffer sizes widely adopted in regional aci studies (Wang et al., 2015; Liu et al., 2017; 2024), enabling cross-validation of results and ensuring that MODIS data averaging effectively captures cloud-aerosol coupling." in Section 2.4 lines 338-364.

3. A basic comment is that frequently the manuscript needed references that were missing. In the following part of the review suggestions on parts that need a reference-or-two will follow. For instance:

3.1) at the end of the sentence in lines 43, 44, and 45, references are needed.

Answer: Added. See the text in the Introduction lines 46-49.

"An increase in CCN concentrations results in a larger number of cloud droplets (N_d), and if the cloud liquid water path (LWP) remains constant, it leads to a reduction in the cloud droplet effective radius (CER) (Twomey, 1977; Feingold et al., 2001)."

3.2) for the arguments in lines 55, 56, and 57: for each of the "satellite observations", "aircraft measurements", "ground-based monitoring", and "numerical simulations" add one-or-two references, to show the importance of the research on atmospheric dust.

Answer: Added. See the text in the Introduction lines 59-62.

"Extensive research on the impact of aerosols on the microphysical properties of clouds has been conducted utilizing satellite observations (Liu et al., 2017; Jia et al., 2022), aircraft measurements (Jia et al., 2019; Zheng et al., 2024), ground-based monitoring (Sarna et al., 2016; Zheng et al., 2020), and numerical simulations (Lee et al., 2025; Li et al., 2008)."

4. 3.3) line 60 and "MODIS". When referencing to instruments, references are required.

Answer: Added. See the text in the Introduction lines 64-66.

"However, optical satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) cannot effectively penetrate cloud layers (King et al., 2003; Kaufman et al., 2005; Remer et al., 2005), making it difficult to directly retrieve the optical properties of aerosols underneath clouds."

3.4) line 97 and "CALIOP". Similar comment with the above.

Answer: Added. See the text in the Introduction lines 108-110.

"In addition, significant progress has been made in research based on Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) data (Winker et al., 2007)."

3.5) line 142 and "particularly during spring": add references on dust climatology over the region of interest.

Answer: Added. See the text in the Section 2.1 line 182.

"Eastern China presents a unique atmospheric laboratory due to its complex aerosol composition - featuring both anthropogenic pollutants from industrial emissions and natural mineral dust transported from Central Asian deserts, particularly during the spring (Proestakis et al., 2018; Liu et al., 2021)."

3.6) line 155 and "cloud systems": add references.

Answer: Added. See the text in the Section 2.2 line 195-197.

"The satellite's equator crossing time is 13:30 (Local time, i.e. in the early afternoon, coinciding with optimal development conditions for continental warm cloud systems (Wang et al., 2014; Liu et al., 2024)."

3.7) lines 204-206: add references.

Answer: Added. See the text in the Section 2.3 lines 288-290.

"Under specific environmental conditions, aerosol particles can transform into CCN or INP, a process primarily determined by their chemical composition and ambient temperature (Bellouin et al., 2020)."

3.8) lines 361-363: add references.

Answer: Added. See the text in the Section 3.2.2 lines 504-506.

4) line 82 and "exhibited positive values over land and negative values over oceans": complete the sentence on positive and negative values of what.

Answer: Corrected. See the text in the Introduction lines 87-90.

"They concluded that the sensitivity of retrieved CER to AOD generally exhibited positive values over land and negative values over oceans, and pointed out that using grids larger than 4°×4° could introduce significant errors due to the spatial variability of aerosol and cloud parameters."

5) line 91 and "only two of these": add which regions.

Answer: Corrected. See the text in the Introduction lines 101-102.

"Their results indicated that only two of these regions, near the coasts of the Gulf of Mexico and the South China Sea, exhibited a positive correlation between CER and AOD."

6) lines 93 and 94 and "aerosol and cloud properties": it would be good to add information on the kind on properties (e.g., physical, chemical, optical, …), naming them.

Answer: Corrected. See the text in the Introduction lines 102-105.

"Similarly, Jones et al. (2009) utilized multi-source remote sensing data and applied a point spread function to derive the mean AOD within a 20 km range, which was designed to match the native 20 km resolution of the corresponding cloud properties (cloud optical thickness, COT; LWP; CER; cloud top pressure, CTP)."

7) line 98 and "calculating aerosol": calculating aerosols what? AOD? a532nm, CCN, ...? Please be more specific.

Answer: Corrected. See the text in the Introduction lines 110-115.

"For instance, Costantino et al. (2010) used CALIOP data to investigate the aerosol influence on CER in stratocumulus clouds over the coastal regions of Namibia and Angola. They performed the analysis by co-locating an aerosol index (based on AOD and the Ångström exponent) with CER within a 150 km buffer zone around CALIOP observations. They found that there was no correlation between aerosol load and CER when aerosol and cloud layers were clearly separated, but a strong correlation when lidar profiles indicated mixing."

8) General the comment on the introduction: frequently in the paragraph studies are mentioned to support the necessity of the study, and this is the approach of the present study. However, in this paper, there are studies that are referencing without properly mentioning the core outcomes and conclusions of the studies, to pave the road for the present study. This leaves a potential reader confused on which is the point of mentioning them if not for also fulfilling the point of delineating the scientific gap. It would be towards the right direction if the authors revisit the introduction and work more on the studies that are mentioned, to bring everything together in the end.

Answer: Thank you for this constructive comment. We fully agree that clarifying the core findings of cited studies and linking them explicitly to the scientific gaps addressed in our work is critical for strengthening the logical flow of the introduction.

To address this issue, we have revised the introduction as follows (See the text in the Introduction lines 84-157):

"Currently, researchers usually use grid methods (such as 1°× 1°, 2°× 2°, etc.) to study the aerosol indirect effects in large areas (Bréon, 2002; Kaufman et al., 2005; Bulgin et al., 2008; Quaas et al., 2008). For instance, Grandey and Stier (2010) estimated the relationship between aerosols and CER on a global scale (60°N~60°S) using multiple spatial resolutions (1°×1°, 4°×4°, 8°×8°, 15°×15°, and 60°×60°). They concluded that the sensitivity of retrieved CER to AOD generally exhibited positive values over land and negative values over oceans, and pointed out that using grids larger than 4°×4° could introduce significant errors due to the spatial variability of aerosol and cloud parameters. Additionally, the study highlighted that, when using grids larger than 4°×4° to investigate the relationship between aerosols and CER, significant errors could be introduced in calculating the aerosol indirect effect index due to the spatial variability of aerosol and cloud parameters.

For studies focusing on smaller regions, researchers often employ a moving window or a fixed area referred to as a buffer zone, within which the distribution of aerosol concentrations is assumed to be uniform. Spatially matched samples are constructed by averaging AOD and cloud parameters within the window or buffer zone. The choice of the window or buffer size is often arbitrary, and existing studies rarely systematically explore how the detection of aci signals is influenced by the size of the area. For example, Yuan et al. (2008) used a 100 km × 100 km moving window to calculate the mean values of AOD and cloud properties to investigate the relationship between aerosols and CER across seven global regions. Their results indicated that only two of these regions, near the coasts of the Gulf of Mexico and the South China Sea, exhibited a positive correlation between CER and AOD. Similarly, Jones et al. (2009) utilized multi-source remote sensing data and applied a point spread function to derive the mean AOD within a 20 km range, which was designed to match the native 20 km resolution of the corresponding cloud properties (cloud optical thickness, COT; LWP; CER; cloud top pressure, CTP). Their study examined the influence of aerosol types, cloud conditions, and atmospheric factors on aerosol indirect effects across six different oceanic regions globally, finding that the sensitivity of cloud properties to AOD varied substantially with regional characteristics. In addition, significant progress has been made in research utilizing observations from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) data (Winker et al., 2007). For instance, Costantino et al. (2010) used CALIOP data to investigate the aerosol influence on CER in stratocumulus clouds over the coastal regions of Namibia and Angola. They performed the analysis by co-locating an aerosol index (based on AOD and the Ångström exponent) with CER within a 150 km buffer zone around CALIOP observations. They found that there was no correlation between aerosol load and CER when aerosol and cloud layers were clearly separated, but a strong correlation when lidar profiles indicated mixing. Costantino et al. (2013) further analyzed the statistical relationship between aerosol concentrations and cloud physical parameters by examining aerosol and cloud properties within a 20 km buffer zone around CALIOP samples, integrating vertical profiles of aerosol and cloud data. Their statistics also clearly showed that cloud micro-physical properties were affected by aerosols when aerosol and cloud layers were mixed, decreasing the CER. It is noted that these two studies by Costantino et al. (2010, 2013) reached consistent conclusions about aci (i.e., aerosols modulate CER when layers interact), by adopting different buffer sizes (150 km vs. 20 km) to target distinct study areas. This demonstrates that the buffer size is tailored to the research objectives rather than through a systematic sensitivity analysis. Wang et al. (2015) revealed an inverse "Twomey" effect between aerosols and CER in eastern China by analyzing aerosol concentrations and CER within a 50 km buffer zone around CALIOP samples. Their results showed that larger CER was associated with high AOD, which was attributed to the feedback of microphysical processes from intense competition for vapor in the presence of high aerosol concentrations and the evaporation of smaller, less hygroscopic, droplets. Similarly, Liu et al. (2017) systematically examined the response mechanisms of warm cloud macro- and microphysical parameters to increasing AOD in the Yangtze River Delta region, also using CALIOP samples within a 50 km buffer zone. They found that the relation between cloud properties and AOD depended on the aerosol abundance, with a different behavior for low and high AOD (i.e. AOD $<$ 0.35 and AOD $>$ 0.35). However, both Wang et al. (2015) and Liu et al. (2017) used a fixed 50 km buffer zone without justifying the choice or exploring how varying buffer sizes might alter the strength or robustness of their findings—a common limitation in regional aci studies. More recently, Liu et al. (2024) quantified the relative importance of aerosols, meteorological parameters and their interactions for cloud properties in the eastern coastal and inland regions of China, utilizing MODIS 1°×1° aerosol and cloud product data. Their study confirmed that CER decreased with the increase in AOD in the moderately polluted atmosphere (0.1 $<$ AOD $<$ 0.3) over the East China Sea, whereas, in contrast, CER increased with increasing AOD in the polluted atmosphere (AOD $>$ 0.3) over the Yangtze River Delta. These studies have provided critical scientific insights into aci at regional scales, but the lack of systematic scale sensitivity analysis—especially for varying window/buffer sizes within the same regional domain—leaves uncertainties about the generalizability of their conclusions.

However, the properties and interaction processes of aerosols and clouds are spatially significantly heterogeneous and scale dependent (McComiskey et al., 2009; McComiskey and Feingold, 2012; Chen et al., 2015; Glotfelty et al., 2020). McComiskey and Feingold (2012) explicitly pointed out that the "scale problem" is a major challenge in quantifying aerosol indirect effects, as the spatial scale of observation can mask or exaggerate the true interaction signals. In previous studies, the definitions of window size and buffer size have often been subjective, inadvertently introducing uncertainties into the research on aci. Although studies have explored the relationship between aerosols and CER across different observational scales, these investigations have primarily focused on larger spatial scales, leaving a gap in sensitivity analysis of aerosol indirect effects at smaller regional scales. For example, Grandey and Stier (2010) focused on global-scale grid resolutions but did not explore the scale dependence within regional domains; Wang et al. (2015) and Liu et al. (2017) used fixed buffer sizes (50 km) without investigating how varying buffer sizes affect the results. Therefore, utilizing multi-source remote sensing data to explore whether and how the aerosol indirect effect depends on observational spatial scales in eastern China is of great significance for developing parameterization schemes that align with the regional characteristics of aci."

These revisions will ensure that each cited study serves a clear purpose in justifying the scientific rationale of our research, helping readers better understand the motivation and novelty of the present work.

9) Section 2.2. and Data used. It would be towards the right direction to add a paragraph describing the degree of uncertainties behind the products used, especially of the CDR, LWP, COT, CTP, and CPI, this addition would be of particular importance, since the uncertainties of the aforementioned products are significantly higher than MODIS AOD.

Answer: Thank you for pointing out this important aspect. We fully agree that explicitly describing the uncertainties of AOD and key cloud products (CER, LWP, COT, CTP, and CPI) is critical for enhancing the transparency and rigor of our study, especially given their relatively higher uncertainty compared to MODIS AOD.

To address this comment, we will add the following paragraph to Section 2.2 "Data used" (lines 201-204 and lines 216-233) to clarify the uncertainty characteristics of the involved products, based on existing validation studies and official product documentation:

"The MODIS AOD (at 550 nm) Level 2 product (10 km × 10 km) has been validated against ground-based remote sensing data and the results show that 69.40% of the MODIS AOD data fall within the expected uncertainty of ± (0.05 + 15 %) over land (Levy et al., 2013)."

"Uncertainties in the MODIS C6.1 cloud parameters over land originate from instrument calibration, atmospheric correction, land surface properties, and model assumptions (Platnick et al., 2017, 2018). For COT, these include scene-dependent Level 1B data errors (1.5%–30%), land surface albedo errors (±15%), and atmospheric correction errors (±20%). The C6.1 algorithm addresses some prior limitations by inheriting C6's optimized lookup table design, which reduces interpolation errors to 0.1%–0.2% for near-nadir views and corrects C5's overestimation of thin-cloud COT (Platnick et al., 2017). CER uncertainties, stemming from solar irradiance error (~4% at 3.7 μm), atmospheric correction, and scattering differences, are mitigated as C6.1 retains C6's separate multi-band reporting, thereby eliminating C5's systematic bias (Platnick et al., 2017). LWP uncertainty is linked to COT/CER retrieval errors and cloud-phase classification accuracy; the latter is improved by C6's voting-based phase algorithm (preserved in C6.1), which reduces misclassification over complex surfaces like vegetation and deserts (Marchant et al., 2015; Platnick et al., 2017). For CTP (1 km resolution), uncertainties from viewing angles and cloud structure are partially countered in C6.1 by assigning fill values when the 1 km retrieval fails, avoiding surface parameter defaults. For land clouds above 3 km, CTP accuracy reaches ~50 hPa (Baum et al., 2012). Finally, CPI adopts C6's weighted voting logic (replacing C5's sequential tree), with C6.1 maintaining an enhanced Phase Agreement Fraction against CALIOP/POLDER data, which reduces uncertainties from weak thin-cloud signals and complex land interference (Marchant et al., 2015; Platnick et al., 2017)"

This revision will provide readers with a clear understanding of the data quality and potential limitations, further strengthening the credibility of our study's findings.

10) line 160: The authors need to add a justification on the reason behind applying the threshold on 1.5, and not for instance 1.4, or 1.6? Add references or as a supplement the analysis made supporting this upper limit.

Answer: Thank you for this insightful comment. To address this concern, we will revise Line 160 and add the following justification in Section 2.2 "Data used" (lines 204-211):

"In this study, AOD larger than 1.5 was excluded from further analysis to mitigate potential retrieval overestimation. This threshold was selected based on two key considerations: (1) Christensen et al. (2017) used MOD06 C6 data (1 km × 1 km) and reported that "large aerosol optical depths remain in the MODIS-observed pixels near cloud edges, due primarily to 3D effects (Varnái and Marshak, 2009) and the swelling of aerosols by higher relative humidity"; (2) the threshold of 1.5 aligns with widely adopted thresholds in regional aerosol-cloud interaction studies over eastern China, where high AOD often coincides with complex surface conditions (e.g., urbanization, heterogeneous land cover) that exacerbate retrieval biases (Wang et al., 2015; Liu et al., 2017, 2021)."

This revision ensures the AOD threshold is not arbitrary but grounded in product characteristics, literature consensus, and data sensitivity, enhancing the transparency and rigor of our data processing steps.

10) Paragraph in lines 180-188: Please revisit the paragraph, the references are not so suitable. When referring to CALIOP and CALIPSO the Winker et al., 2009, 2010, and 2013 are the most suitable ones, the Winker et al., 2003 should change. Moreover, the Stephens et al., 2002 is at the early steps of the A-Train and the authors should possibly add more updated references. Finally, CALIOP is not the "first" space-based lidar in space, so remove please correct this part.

Answer: Corrected. See the text in the Section 2.2 lines 249-255.

"CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) operates within the A-Train constellation alongside the Aqua satellite and other NASA Earth-observing platforms. The primary instrument aboard CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). CALIOP is a two-wavelength, polarization-sensitive lidar specifically designed to provide high-resolution vertical profiles of aerosols and clouds on a global scale (Winker et al., 2009). The mission and its lidar instrument are described in Winker et al. (2009), and the associated Level 1 data products are detailed in Winker et al. (2010)."

11) Table 1: add more information on the products used, especially in terms of CALIOP, the list is not complete I guess, I am left of the impression that more observations and products were applied than just the coordinates.

Answer: Thanks for your reminder! Just to clarify: In this study, we only used latitude, longitude, and time information from CALIOP. This is because CALIOP and MODIS are both part of the A-Train satellite constellation, and their observation time difference is controlled within 1–2 minutes. This coordinated observation ensures that the MODIS aerosol (AOD) and cloud parameter data corresponding to the CALIOP positioning buffer are "quasi-simultaneous", which effectively avoids interferences such as aerosol diffusion and cloud physical state evolution caused by observation time lags—an advantage that positioning methods like random grid points or ground stations cannot match. Subsequently, we calculated the mean values of MODIS AOD and cloud parameters within each CALIOP positioning buffer to conduct correlation analysis of aerosol indirect effects. We also added the text in the Section 2.2 lines 261-263.

"This temporal synchronization guarantees data consistency when extracting coincident measurements, avoiding interferences such as aerosol diffusion and cloud evolution caused by observational time lags—an advantage unparalleled by positioning methods like random grid points and ground-based stations."

12) end of section 2.3: It would be fair to the approach and the readers to provide a paragraph reporting the assumptions and uncertainties of the methods/equations, and as such the limitations, in order to facilitate also future studies.

Answer: Thank you for this valuable suggestion. We fully agree that explicitly outlining the key assumptions, inherent uncertainties, and limitations of the data processing methods in Section 2.3 is essential for enhancing the transparency of our study and providing meaningful references for future research.

To address this comment, we have added the following paragraph at the end of Section 2.3 lines 316-327:

"This method quantifies the sensitivity of CER and N_d to AOD variations via linear regression in log-log space, using Eq. 1 and Eq. 2, respectively. Its core assumptions, uncertainties, and limitations are highly consistent: both rely on AOD as an aerosol proxy variable, assume constant cloud liquid water content and a linear sensitivity relationship, and depend on the reliability of satellite-retrieved parameters (Feingold et al., 2001; Gryspeerdt et al., 2023). However, AOD cannot distinguish aerosol size and hygroscopicity, retrieval errors are substantial in clean conditions, and linear fitting fails to capture nonlinear/non-monotonic responses. Both methods are constrained by satellite retrieval biases, limited scenario applicability (only valid for specific homogeneous clouds and aerosol types), the omission of key modulating factors (dynamical conditions, aerosol type) and feedback processes, and can only assess first-order direct effects. Reliability requires scenario constraints and uncertainty analysis; the only nuances come from the target variable (CER vs. N_d), which do not alter the shared methodological limitations."

13) Section 2.4 line 236: at some point the comparison of clouds' horizontal extend with the spatial homogeneity of aerosols should be discussed.

Answer: Thank you for highlighting this critical point. We fully agree that discussing the relationship between cloud horizontal extent and aerosol spatial homogeneity is essential for justifying the multi-scale analysis framework in Section 2.4, as it directly affects the validity of assuming aerosol homogeneity within buffer zones.

To address this comment, we will add the following discussion in Section 2.4 lines 348-364:

"Previous observations indicate that the typical horizontal scale of cloud clusters ranges from tens to hundreds of kilometers (Zhang et al., 2024; Cai et al., 2022), supported by CloudSat/CALIPSO satellite data showing power-law distributed cloud scales (10-1000 km fitting range) covering major cloud types (Zhang et al., 2024) and regional evidence of consistent multi-season, multi-latitude cloud extents (Cai et al., 2022). Meanwhile, aerosol spatial homogeneity varies with distance: local-scale aerosols (≤ 50 km) exhibit high homogeneity due to consistent sources and stable diffusion, while regional-scale aerosols (> 100 km) show enhanced heterogeneity from multi-source mixing and atmospheric transport (Hassan et al., 2024; Mohebalhojeh et al., 2026). Thus, the 10–300 km buffer range covers both cloud characteristic scales and the aerosol homogeneity transition range, ensuring that MODIS data averaging effectively captures cloud-aerosol coupling. This range avoids insufficient MODIS pixel coverage due to excessively small buffer sizes (< 10 km). It also prevents conflation between regional meteorological variations and local aci signals arising from overly large buffer sizes (> 300 km), as synoptic-scale circulation and other regional meteorological changes may interfere with local aci signals (Quaas et al., 2010). Meanwhile, this range aligns with the 50–150 km buffer sizes widely adopted in regional aci studies (Wang et al., 2015; Liu et al., 2017; 2024), enabling cross-validation of results and ensuring that MODIS data averaging effectively captures cloud-aerosol coupling."

14) Central hypothesis of the comparison between the two periods is that LWP is more or less similar, allowing comparison between AOD and CER/N_d in terms of spatial sensitiveness. Please add at some point discussion on the degree that this hypothesis holds.

Answer: Thank you for this critical observation. We fully agree that verifying the similarity of LWP characteristics between the two study periods (2008–2014 and 2015–2022) is essential to validate the core hypothesis of our comparative analysis—ensuring that differences in aerosol-cloud sensitivity (S_{CER}/S_{Nd}) are primarily driven by changes in AOD rather than variations in LWP.

To address this comment, we will add the following discussion in Section 4.1 lines 636-651:

"The central hypothesis of this study—that LWP is relatively consistent between the two periods (2008–2014 and 2015–2022), supporting valid comparisons of the spatial sensitivity of AOD-CER relationships—is well-supported by the following analysis. The differences in the mean, median, 25th, and 50th percentiles of LWP between the two periods are all less than 5%, indicating a stable overall water vapor supply level. The spatial patterns of high-LWP regions (e.g., southeastern areas) and low-LWP regions (e.g., the mountainous areas in northern Shanxi) remained stable across the two periods (see Supplement Figure S1), demonstrating LWP spatial distribution characteristics are highly consistent. The sample proportions of LWP in the rapid growth regime are 59.30% (period 1: 0–55 g/m²) and 55.36% (period 2: 0–50 g/m²), while those in the decreasing regime are 29.64% (period 1: 55–135 g/m²) and 24.59% (period 2: 50–100 g/m²), suggesting that there is no systematic temporal shift in the LWP distribution. Meanwhile, short-term fluctuations are smoothed by multi-year averaging and large-sample statistics, resulting in a weak indirect impact of aerosols on LWP (LWP only increased by 5.6%, much smaller than the 24% decrease in AOD). Additionally, LWP-stratified analysis further isolates interference. The validation of the core hypothesis provides a reliable premise for accurately quantifying the impact of aerosol concentration changes on the sensitivity of cloud parameters and their spatial scale dependence.”

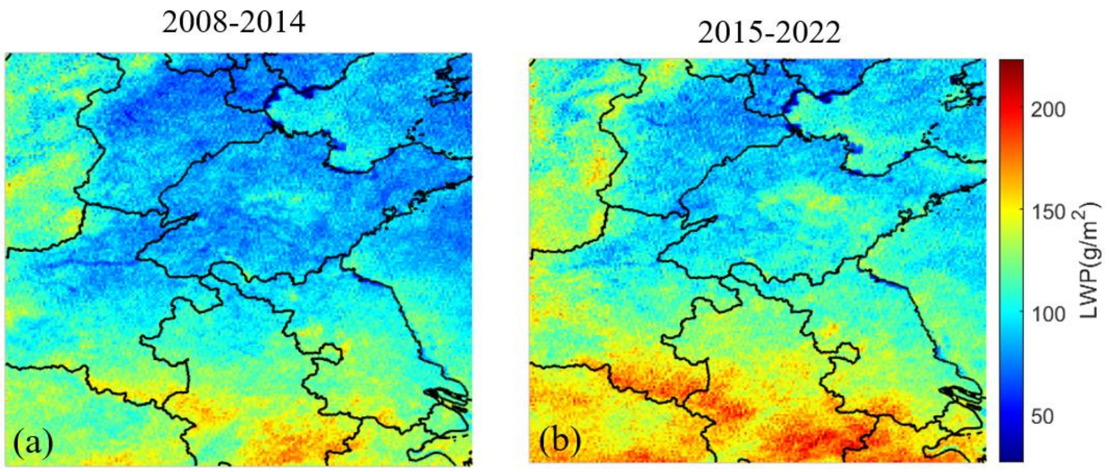

Figure S1. Spatial distributions of LWP averaged over the years 2008-2014 (a) and 2015-2022 (b) over the study area. The lines are provincial borders and the names of provinces mentioned in the text are indicated in Fig. 3(f).

15) Lines 261-262 and lines 269-270: please add at least at one map the Hebei, Shandong, Shanxi, and Anhui provinces at a map, not everyone is familiar with the geographical areas and provinces in terms of where they are located.

Answer: Corrected.

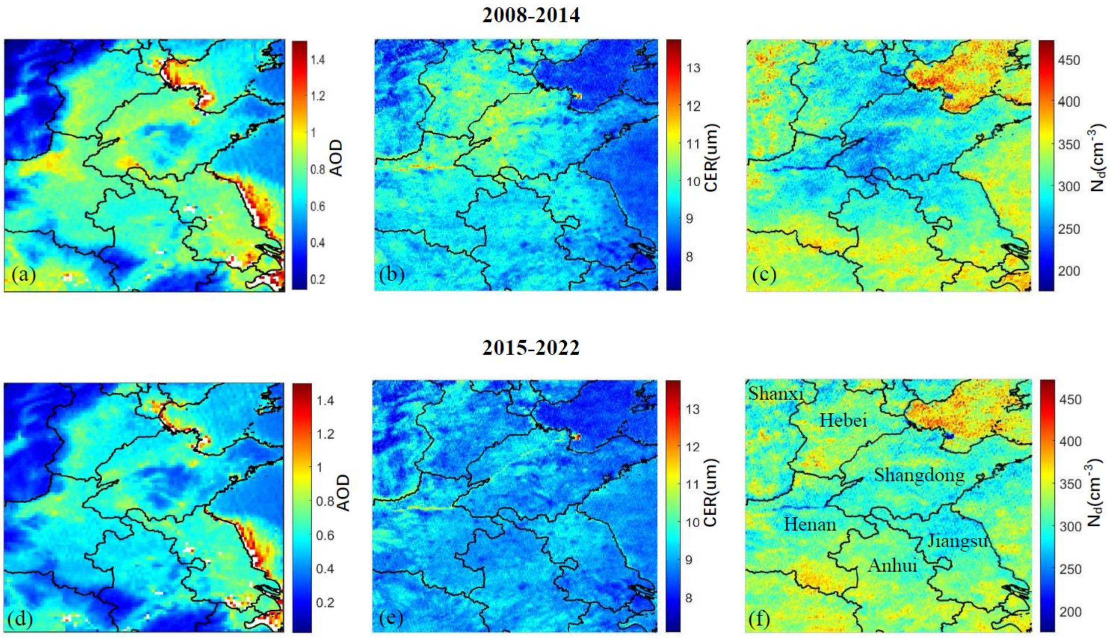

Figure 3. Spatial distributions of AOD (a, d), CER (b, e) and N_d (c, f), averaged over the years 2008-2014 (top row) and 2015-2022 (bottom row) over the study area.

16) line 268: correct ".,".

Answer: Corrected.

17) Lines 314-318: When providing results of the analysis discuss on the reasons "why" behind the results is of significance. A connection with theory is missing in this section. The paper would benefit by adding a few lines at the end of the section.

Answer: Thank you for this valuable suggestion. We fully agree that explaining the "why" behind the results—by linking them to aerosol-cloud interaction theory — is critical for deepening the scientific insight of Section 3.2.1 (Rapid CER growth regime) and enhancing the paper's rigor.

To address this, we will add the following lines at the end of Section 3.2.1 lines 461-463 and Section 4.2 lines 662-673, connecting the observed scale-dependent S_{CER} patterns to theoretical mechanisms:

"The decrease of $|S_{CER}|$ with increasing study area is mechanistically tied to scale-dependent aerosol indirect effect theory and meteorological confounding (Quaas et al., 2009; McComiskey & Feingold, 2012)."

"The results from this study suggest that AOD-cloud property correlations in large study areas are susceptible to meteorological confounding effects (Quaas et al., 2010; Boucher and Quaas, 2012; Gryspeerdt et al., 2014; Liu et al., 2024). Theoretically, aerosol regulation of cloud microphysics is strongly local: smaller domains (e.g., 4°×4°) feature homogeneous meteorological conditions (humidity, updrafts), preserving undiluted aerosol-cloud interaction signals and yielding larger $|S_{CER}|$ (pronounced Twomey effect). In contrast, expanded domains (e.g., 10°×10°) encompass heterogeneous meteorological conditions (circulation differences, boundary layer variability) that independently modulate cloud droplet growth. For example, strong updrafts enhance liquid water supply, offsetting aerosol-induced radius reduction (Altaratz et al., 2014), weakening aerosol-CER correlations and reducing $|S_{CER}|$. Consistent with Grandey & Stier (2010), large-scale domains introduce "dilution bias" via non-target meteorological variability. This scale-dependent confounding mechanism elucidates uncertainties in aerosol indirect effect assessments at regional scales."

18) Lines 369-371: In general it is missing an explanation on the mechanisms resulting to the observed patterns, here are results provided without any connection with theory or at least some brief discussion. The section can be significantly improved.

Answer: Thank you for this constructive feedback. We fully agree that supplementing mechanistic explanations—linking the observed S_{CER} patterns in the decreasing LWP regime to aerosol-cloud interaction theories and physical processes—is critical for enhancing the scientific depth of Section 3.2.2 and addressing the "why" behind the results.

To address this gap, we will add the following discussion at the end of Section 3.2.2 lines 514-516 and Section 4.1 lines 602-624, integrating theoretical mechanisms with the observed results:

“This pattern highlights the dominant role of LWP in regulating aerosol-cloud interaction sensitivity, with AOD variations further modulating the magnitude of such differences.”

“Comparative analysis of scale-conditioned S_{CER} across LWP regimes in periods 1 and 2 revealed markedly enhanced sensitivity of S_{CER} to AOD in the second LWP regime. There is a trade-off between AOD and LWP when the amount of water vapor is insufficient and CER becomes smaller. As suggested by Costantino et al. (2013), the LWP response to aerosol invigoration is influenced by two competing mechanisms: a drying effect caused by enhanced entrainment of dry air at cloud top (dominant in optically thin clouds) and a moistening effect from precipitation suppression (dominant in optically thick clouds). For larger LWP, the supply of cloud water is sufficient, and the increase in aerosol number concentrations significantly affects the distribution of cloud droplet number concentrations and sizes, enhancing the sensitivity of CER to AOD. For small aerosol concentrations, the values of $|S_{CER}|$ (Figure 5b, 7b) decreased overall with expanding buffer size within the same study area. For fixed buffer size, $|S_{CER}|$ decreased as the study area increased, and the ranges of $|S_{CER}|$ values across different study area showed a convergent pattern, typically remaining small (close to zero). During the high AOD period (2008–2014), anthropogenic emissions and dust transport provided abundant CCN, laying the material foundation for aerosol-cloud interactions. This enhanced the synergistic effect of “sufficient liquid water + abundant CCN” in the second LWP regime, amplifying the difference in S_{CER} between the two LWP regimes. In the period of decreasing AOD (2015–2022), following the implementation of clean air policies (de Leeuw et al., 2021; 2023), CCN concentration decreased (Wang et al, 2023), weakening the direct impact of aerosols on CER. However, the LWP-driven microphysical differences persisted, so S_{CER} in the second regime remained significantly smaller than that in the first regime, albeit with a smaller difference. Additionally, the complexity of aerosol types during the high AOD period (e.g., mixing of anthropogenic pollutants and natural dust) may have adjusted the value of S_{CER}, but did not alter the dominant role of LWP. This aligns with the theory that “aerosol indirect effects are jointly regulated by concentration and type” (Liu et al., 2017).”

19) Section 3.3: At some point discussion of AOD has to be included, in terms of composition. The aerosol composition resulting to the AOD over the two periods may have significantly changed due to the policies imposed, therefore the impact of AOD on clouds may be very different, even for exact same AOD values, since the relative percentage of different aerosol species will be different. Add at least some discussion on this aspect, to be fair with the analysis, the hypothesis that are made, and the readers.

Answer: Thank you for highlighting this important aspect. We fully agree that discussing potential changes in aerosol composition between the two periods (2008–2014 and 2015–2022) is critical for contextualizing the observed S_{Nd} patterns—since aerosol composition directly affects CCN activity and thus the impact of AOD on cloud microphysics, even for identical AOD values.

To address this gap, we will add the following discussion in Section 3.3 lines 560-575, linking aerosol composition changes to policy impacts and cloud sensitivity:

“The chemical composition of aerosols, which directly affects AOD and CCN activation efficiency, underwent significant changes between the two periods due to policy interventions. During 2008–2014, aerosols over eastern China were dominated by sulfate, which accounted for 30%–40% of the $PM_{2.5}$ mass (Huang et al., 2014; Zheng et al., 2018). Given the strong hygroscopicity of sulfate-dominated aerosols (Zhang et al., 2012; Liu et al., 2023), their CCN activation efficiency was likely high, which may have provided a critical physical basis for the aerosol-cloud indirect effect (Lee et al., 2009). In the period of 2015–2022, driven by policies such as the Air Pollution Prevention and Control Action Plan (Zheng et al., 2018), the chemical composition of aerosols underwent a structural transition. Specifically, the mass fraction of sulfate dropped sharply to 15%–25% with an absolute concentration reduction of more than 50%, while the relative proportions of nitrate, carbonaceous aerosols (i.e., organic carbon (OC) and black carbon (BC)), and secondary organic aerosols (SOA) showed an increasing trend (Huang et al., 2014; Zheng et al., 2018). As these components generally exhibit weaker hygroscopicity compared with sulfate (Zhang et al., 2012; Liu et al., 2023), such a compositional shift might have led to a decrease in CCN activation efficiency under the same AOD conditions, thereby potentially weakening the sensitivity of cloud droplet number concentration to AOD and altering the intensity and mode of aerosol-cloud interactions to a certain extent (Lee et al., 2009)."

20) Section 4. The discussion is well-written. However, some of the points raised should also appear accompanying the results and the discussion on the figures, and not appearing in this section for the first time.

Answer: We thank the reviewer for the positive feedback on the discussion and for this constructive suggestion. We have carefully integrated the key discussion points raised in Section 4 into the corresponding results sections and figure captions throughout the manuscript to ensure a more logical flow. The revisions are now reflected in the updated manuscript for the reviewer's inspection.

4 Discussion

4.1 The importance of liquid water path constraint

LWP is a critical parameter governing cloud radiative properties (Murray-Watson et al., 2022). The quantification of albedo effects strongly depends on the spatial scale and the LWP. Neglecting LWP constraints in aerosol-cloud interaction studies can weaken microphysical signals, leading to underestimation of radiative forcing (McComiskey et al., 2012). To address this, we first systematically investigated the dynamic relationship between CER and LWP before analyzing CER sensitivity to AOD. The results demonstrate pronounced CER sensitivity to LWP variations, which can be categorized into three distinct regimes (Figure 4):

In the first LWP regime, CER increases rapidly with LWP, i.e. the evolution of CER is predominantly driven by changes in LWP. This dominance may lead to overestimation of the influence of the AOD on CER (Liu et al., 2021).

In the second LWP regime, CER decreases with increasing LWP. In this regime, the regulatory effect of LWP on CER weakens significantly, and CER variations become increasingly governed by aerosol-related processes, indicating the growing dominance of aerosol indirect effects.

The third regime contains an insufficient number of CER observations to yield statistically significant results, which excludes the analysis of the sensitivity of CER to AOD.

Comparative analysis of scale-conditioned S_{CER} across LWP regimes in periods 1 and 2 revealed markedly enhanced sensitivity of S_{CER} to AOD in the second LWP regime. There is a trade-off between AOD and LWP when the amount of water vapor is insufficient and CER becomes smaller. As suggested by Costantino et al. (2013), the LWP response to aerosol invigoration is influenced by two competing mechanisms: a drying effect caused by enhanced entrainment of dry air at cloud top (dominant in optically thin clouds) and a moistening effect from precipitation suppression (dominant in optically thick clouds). For larger LWP, the supply of cloud water is sufficient, and the increase in aerosol number concentrations significantly affects the distribution of cloud droplet number concentrations and sizes, enhancing the sensitivity of CER to AOD. For small aerosol concentrations, the values of $|S_{CER}|$ (Figure 5b, 7b) decreased overall with expanding buffer size within the same study area. For fixed buffer size, $|S_{CER}|$ decreased as the study area increased, and the ranges of $|S_{CER}|$ values across different study area showed a convergent pattern, typically remaining small (close to zero). During the high AOD period (2008–2014), anthropogenic emissions and dust transport provided abundant CCN, laying the material foundation for aerosol-cloud interactions. This enhanced the synergistic effect of "sufficient liquid water + abundant CCN" in the second LWP regime, amplifying the difference in S_{CER} between the two LWP regimes. In the period of decreasing AOD (2015–2022), following the implementation of clean air policies (de Leeuw et al., 2021; 2023), CCN concentration decreased (Wang et al, 2023), weakening the direct impact of aerosols on CER. However, the LWP-driven microphysical differences persisted, so S_{CER} in the second regime remained significantly smaller than that in the first regime, albeit with a smaller difference. Additionally, the complexity of aerosol types during the high AOD period (e.g., mixing of anthropogenic pollutants and natural dust) may have adjusted the value of S_{CER}, but did not alter the dominant role of LWP. This aligns with the theory that "aerosol indirect effects are jointly regulated by concentration and type" (Liu et al., 2017).

The larger S_{CER} observed at larger spatial scales (Figures 5 and 7) may be attributed to meteorological confounding effects. In addition, clouds with larger LWP are usually associated with strong updrafts (such as convective clouds), and stronger turbulence and vertical transport will bring more aerosols into the clouds, increasing CCN concentration and a decrease in particle size, making them more sensitive to changes in AOD (Jones et al., 2009; Han et al., 2022; Fan et al., 2025). Therefore, this phenomenon is the result of the combined action of cloud microphysical processes (CCN activation, cloud droplet competition growth) and dynamic processes (updrafts, turbulent mixing). If the characteristics of aerosols (such as composition) change in the second LWP regime, this sensitivity may be further amplified. Consequently, the LWP-stratified S_{CER} quantification framework enables precise characterization of scale-dependent aerosol-cloud interactions, providing robust physical insights for climate effect assessments and effectively reducing uncertainties in future climate projections.

The central hypothesis of this study—that LWP is relatively consistent between the two periods (2008–2014 and 2015–2022), supporting valid comparisons of the spatial sensitivity of AOD-CER relationships—is well-supported by the following analysis. The differences in the mean, median, 25th, and 50th percentiles of LWP between the two periods are all less than 5%, indicating a stable overall water vapor supply level. The spatial patterns of high-LWP regions (e.g., southeastern areas) and low-LWP regions (e.g., the mountainous areas in northern Shanxi) remained stable across the two periods (see Supplement Figure S1), demonstrating LWP spatial distribution characteristics are highly consistent. The sample proportions of LWP in the rapid growth regime are 59.30% (period 1: 0–55 g/m^2) and 55.36% (period 2: 0–50 g/m^2), while those in the decreasing regime are 29.64% (period 1: 55–135 g/m^2) and 24.59% (period 2: 50–100 g/m^2), suggesting that there is no systematic temporal shift in the LWP distribution. Meanwhile, short-term fluctuations are smoothed by multi-year averaging and large-sample statistics, resulting in a weak indirect impact of aerosols on LWP (LWP only increased by 5.6%, much smaller than the 24% decrease in AOD). Additionally, LWP-stratified analysis further isolates interference. The validation of the core hypothesis provides a reliable premise for accurately quantifying the impact of aerosol concentration changes on the sensitivity of cloud parameters and their spatial scale dependence.

4.2 Scale dependence of cloud parameters sensitivities to aerosol variations

Extensive studies have demonstrated a significant spatial scale dependence of aerosol indirect effects (McComiskey et al., 2012; Possner et al., 2016; Glotfelty et al., 2020; Ekman et al., 2023). Failure to explicitly define the scale-dependent behavior of aerosol indirect effects may introduce systematic biases and inconsistencies in subsequent process analyses. Based on satellite observations, this study confirms statistically significant negative correlations between CER and AOD, as well as positive correlations between N_d and AOD during periods with different aerosol concentrations, aligning with classical aerosol-cloud interaction theory (Quaas et al., 2009). Analysis of scale-conditioned S_{CER} and S_{Nd} reveals that for fixed buffer size, an increase in the size of the study area leads to a systematic reduction in S_{CER} (less negative) and S_{Nd}, corroborating the nonlinear attenuation of aerosol signals with spatial domain expansion (Quaas et al., 2009). The results from this study suggest that AOD-cloud property correlations in large study areas are susceptible to meteorological confounding effects (Quaas et al., 2010; Boucher and Quaas, 2012; Gryspeerdt et al., 2014; Liu et al., 2024). Theoretically, aerosol regulation of cloud microphysics is strongly local: smaller domains (e.g., 4°×4°) feature homogeneous meteorological conditions (humidity, updrafts), preserving undiluted aerosol-cloud interaction signals and yielding larger $|S_{CER}|$ (pronounced Twomey effect). In contrast, expanded domains (e.g., 10°×10°) encompass heterogeneous meteorological conditions (circulation differences, boundary layer variability) that independently modulate cloud droplet growth. For example, strong updrafts enhance liquid water supply, offsetting aerosol-induced radius reduction (Altaratz et al., 2014), weakening aerosol-CER correlations and reducing $|S_{CER}|$. Consistent with Grandey & Stier (2010), large-scale domains introduce "dilution bias" via non-target meteorological variability. This scale-dependent confounding mechanism elucidates uncertainties in aerosol indirect effect assessments at regional scales.

Multi-scale spatial analysis identifies different optimal buffer sizes for S_{CER} and S_{Nd} in different periods. These findings align closely with satellite-based aerosol indirect effect studies (Wang et al., 2015; Liu et al., 2017), providing critical scale benchmarks for satellite product validation. Wang et al. (2015) reported an inverse "Twomey" effect between aerosols and CER in eastern China by analyzing aerosol and CER within a 50 km buffer zone around CALIOP samples. Similarly, Liu et al. (2017) systematically examined the response mechanisms of warm cloud macro- and microphysical parameters to increasing AOD in the Yangtze River Delta region, also using CALIOP samples within a 50 km buffer zone. Present study further shows that, as aerosol concentrations decrease, S_{CER} values across different study areas with the same buffer size exhibit convergence characteristics, with generally smaller S_{CER} (closer to zero). This indicates a significant weakening of aerosol-cloud interaction intensity and reduced spatial extent dependency in low aerosol loading conditions. This phenomenon is consistent with the simulated behavior of aerosol-limited cloud regimes, where aerosol-cloud interactions are quantitatively modulated by moisture availability and lose their sensitivity to large-scale dynamical stability, leading to a weaker and more homogeneous effect (Zhao et al., 2025).

By systematically quantifying the scale-response characteristics of aerosol indirect effects, this work not only elucidates the dynamic scale behavior of aerosol-cloud interactions but, more critically, establishes criteria for determining optimal buffer size in regional aerosol indirect effect studies. Such advancements provide actionable insights for refining parameterization schemes in climate models, thereby enhancing their predictive reliability.

4.3 Contrasting sensitivity patterns of cloud parameters in response to AOD

A comprehensive comparison of the sensitivity S_{CER} and S_{Nd} reveals that the responses of CER and N_d to AOD exhibit distinct yet inherently interconnected characteristics. These characteristics are jointly modulated by spatial scale and LWP regimes (Figs. 5, 7, 8; Supplements Tables 1–2), which profoundly reflect the core microphysical mechanisms of aerosol-cloud interactions. Details are elaborated as follows:

4.3.1 Core differences in response modes between S_{CER} and N_d to AOD

S_{CER} is consistently negative across both periods and all LWP regimes ($-0.33<S_{CER}<0$) (Figs. 5, 7; Supplement Table 1), indicating that an increase in AOD leads to a decrease in CER. This aligns with the core principle of the Twomey effect (Twomey, 1977; Feingold et al., 2001). The values of $|S_{CER}|$ are larger in the second LWP regime than in the first regime, reflecting stronger aerosol modulation of cloud microphysical properties when liquid water is abundant (McComiskey & Feingold, 2012). In contrast, S_{Nd} maintains a significant positive correlation with AOD across all scenarios ($0<S_{Nd}<1$) (Fig. 8; Supplement Table 2), confirming that higher AOD directly promotes CCN activation and thereby increases cloud droplet number concentration (Andreae, 2009). S_{Nd} is larger in small-scale study areas (e.g., 4°×4°) and small buffer zones, with a maximum value of 0.45 in the first period, indicating greater sensitivity of cloud droplet number to aerosol loading at fine spatial scales.

4.3.2 Synergistic modulation of AOD and spatial scale

Using the LWP interval corresponding to S_{Nd} ($0 < LWP \leq 200$ g/m²) as a benchmark, comparisons between the two periods (incorporating average values of S_{CER} across two LWP regimes) reveal distinct characteristics:

For the small-scale study area (4°×4°): In period 1, the average $|S_{CER}|$ across two LWP regimes is 0.271 (0.2232 for the 0–55 g/m² LWP regime, 0.3189 for the 55–135 g/m² LWP regime) and S_{Nd}=0.4496, both significantly higher than those in period 2 (average $|S_{CER}|$=0.154, with 0.0863 for 0–50 g/m² LWP regime and 0.2212 for 50–100 g/m² LWP regime; S_{Nd}=0.2903). The negative correlation between AOD and CER is more significant in period 1, as sufficient CCN in small-scale areas amplifies both cloud droplet number increase and size reduction, enhancing the Twomey effect.

For the medium-to-large scale study areas (6°×6°, 8°×8°, 10°×10°): In period 1, the average $|S_{CER}|$ across two LWP regimes is 0.1683 (0.1305 for 0–55 g/m², 0.2061 for 55–135 g/m²), 0.13065 (0.1026 for 0–55 g/m², 0.1587 for 55–135 g/m²), and 0.1067 (0.0858 for 0–55 g/m², 0.0885 for 55–135 g/m²), respectively, all higher than the corresponding values in period 2 (0.1516, 0.1246, 0.0985). However, S_{Nd} in period 1 (0.2430, 0.2050, 0.1430) is lower than that in period 2 (0.2960, 0.2680, 0.1740), with no significant difference in the negative correlation between AOD and CER between the two periods.

This characteristic indicates that meteorological confounding effects are enhanced at larger scales, weakening the regulation of S_{Nd} by aerosols, while at small scales the aci is directly driven by AOD levels.

4.3.3 Implications for aerosol indirect effects

The differences and interconnections between S_{CER} and S_{Nd} highlight that aerosol indirect effects are dominated by coupled microphysical processes: Aerosol-induced increases in CCN first enhance N_d through positive S_{Nd}, and then reduce CER through negative S_{CER} under constant LWP conditions. The scale-dependent attenuation of both sensitivities and their modulation by LWP indicate that quantifying aerosol indirect effects requires full consideration of spatial scales and the key role of liquid water, providing observational basis for optimizing climate model parameterization schemes.

4.4 Limitations and future perspectives

This study has three significant limitations. Firstly, similar to most previous studies (Wang et al., 2015; Liu et al., 2021), this study only utilized MODIS data with a resolution of 10 km to explore scale effects, ignoring finer or coarser resolution data. Therefore, using a 10 km buffer size as the minimum observation unit, this limitation makes the indirect effects of aerosols on smaller scales still unknown, which may lead to inaccurate evaluation of aerosol indirect effects. Therefore, future research can improve the sensitivity of aerosol indirect effects to scale changes by using observation data with higher accuracy or model simulations. Secondly, the current research focuses on the influence of buffer size and study areas, the potential impact of spatial aggregation methods (especially zoning directionality) on the quantitative results of aerosol indirect effects has not been systematically evaluated. Future research should further investigate the sensitivity of aerosol indirect effects to zoning direction. Moreover, the current study employs a uniform buffer size for both aerosol and cloud parameters, failing to account for potential interaction effects arising from discrepancies of buffer size between them. Therefore, clarifying scale dependence will avoid directly extrapolating local observation results to a larger study area when downscaling climate models or formulating regional environmental policies.

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