Response to the Comments of Referees

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We thank the reviewers and the editor for providing helpful comments to improve the manuscript. We have revised the manuscript according to the comments and suggestions of the referees.
The referee's comments are reproduced (black) along with our replies (blue). All the authors have read the revised manuscript and agreed with the submission in its revised form.

Anonymous Referee #2

Review of 'How meteorological conditions influence aerosol-cloud interactions under different pollution regimes'

This study uses WRF-Chem to simulate marine liquid clouds near the Eastern China Ocean during a selected winter period. The experiments are designed to examine aerosol effects on cloud and precipitation by comparing clean versus polluted scenarios. Results show that aerosols extend cloud lifetime in moist conditions but shorten it in dry conditions. In the polluted regime, continental aerosols lead to higher Nd and CLWP and smaller CER, while precipitation responses are mixed overall. Under the clean regime, aerosol activation is efficient and responses are clearer with supersaturation. In polluted conditions, clouds exhibit mixed responses tied to different cloud processes, reflecting regime-dependent ACI sensitivity.

While the overall narrative and logic read fine, I found multiple occasions where the interpretation and discussion are rather vague or misleading. As such, I have questions and comments on technical and interpretive details. The comments below include several general comments and more specific comments, laid out in the narrative sequence when reading the manuscript.

We deeply appreciate the reviewer's constructive comments and useful suggestions. We have carefully considered the concerns regarding interpretation and discussion, and have refined the manuscript accordingly. Our detailed point-by-point responses are provided below (in blue).

General Comments

In the Introduction, please situate this work within prior LES efforts (WRF-SBM, WRF-Chem, SAM, etc.) over the East China Ocean and synthesize what they concluded about ACI. Then clarify the remaining gap and why a chemistry-aware framework is needed here: specifically, what does WRF-Chem capture that a physics-only perturbation of aerosol number in WRF/WRF-SBM cannot? Because much of your analysis emphasizes dynamical/thermodynamic linkages, please consider discussing

how chemical pathways modify those linkages and how your design advances beyond prior 'simple number-perturbation' studies.

We conducted a review on the ACI modeling studies over the East China Ocean and found that although ACI is a research hotspot, there are not many studies with the research area set in the East China Ocean, and most are based on a chemistry-aware framework. For example, Saleeby et al. (2010) used a cloud-resolving model to explore the response of cloud and precipitation microphysics to aerosols, while Bennartz et al. (2011) and Guo et al. (2022) used WRF-Chem to investigate the impact of continental pollution on ECO cloud microphysics and the impacts of anthropogenic and sea salt aerosols on a heavy rainfall event, respectively. These studies pointed out the increase of N_d and the decrease of precipitation caused by continental aerosols, as well as the reduction of N_d and the increase of CER due to large particles suppressing the activation of small particles. In our study, the analysis of the effects of continental aerosols generally agrees with the former, but by tracing ACI under different environments, we pointed out cases in which continental aerosols lead to enhanced precipitation. As for the latter, we did not separately analyze the impacts of large and small particles, but the revealed suppression of small particle activation by a large number of medium-sized droplets under high supersaturation, resulting in a decrease of N_d and an increase of CER, is similar to their findings.

We broadened our review objectives and, based on relevant ACI modeling studies, explained why a chemistry-aware framework is needed. Through physics-only perturbation of aerosol, related studies, on the basis of the well-established fundamental theories of ACI, explored the dependence of aerosol activation on aerosol properties and meteorological conditions (Reutter et al., 2009; Tang et al., 2024), the variation of the Twomey effect with cloud dynamics and pollution levels (Andrejczuk et al., 2014; Prabhakaran et al., 2023; Tang et al., 2024), as well as the variation of rapid adjustments with cloud properties (Heikenfeld et al., 2019; Jiang et al., 2023; Prabhakaran et al., 2023; Tang et al., 2024). This method effectively isolates the influence of external factors (such as large-scale dynamics, radiation, chemical processes, and emissions), diagnoses the response of cloud microphysics to aerosols, and deepens the understanding of ACI. However, studies based solely on physics-only perturbation of aerosol have certain limitations, for example: (1) difficulty in reproducing the spatiotemporal variation of aerosol properties (such as concentration, size distribution, and chemical composition), which may lead to distortion of activation simulations (George et al., 2015; Hodzic et al., 2023); (2) the absence or inaccuracy in treating aerosol-related physical processes (such as resuspension, wet deposition, and thermodynamic and dynamic changes induced by aerosols) may result in quantitative or even qualitative biases in ACI signals (Ahmadov, 2016; Briant et al., 2017); (3) difficulty in direct comparison with observations, leading to insufficient verifiability of the results.

Compared with physics-only perturbation of aerosol, the chemistry-aware framework can effectively address the issues of accuracy in aerosol treatment and verifiability. Based on the chemistry-aware framework, related studies have conducted extensive quantitative and qualitative research on ACI (Saleeby et al., 2010; Bennartz et al., 2011; Liu et al., 2020; Guo et al., 2022; Haghighatnasab et al., 2022), providing strong support for our understanding of the impacts of aerosols on clouds and the influencing factors of ACI under factual scenarios. However, these studies also have some limitations:

(1) compared to physics-only perturbation of aerosol, their ACI analyses introduce external interferences such as radiation and aerosol-induced meteorological changes; (2) analyses of ACI sensitivity to individual factors are often confounded by co-varying influences, leading to uncertainties in signal separation; (3) quantitative and qualitative conclusions derived from case studies may not hold under different conditions; and (4) bulk microphysical parameterizations may distort ACI signals, both quantitatively and qualitatively. In this study, we controlled the uncertainties arising from the above issues from the perspectives of technical approaches, experimental design, and analytical methods: (1) avoidance of ARI interference in ACI analyses through disabling radiative effects in simulations and ensuring consistency of meteorological conditions across experiments through four-dimensional data assimilation; (2) examination of ACI responses to the co-variation of different meteorological factors and of meteorological factors and aerosols and enhancement of ACI signal detectability through large N_a differences between Control and Clean experiments; (3) selection of a case exhibiting significant co-variations in meteorology, aerosols, and clouds to support a relatively comprehensive analysis; and (4) use of high-resolution spectral bin microphysics modeling to better represent realistic ACI processes. These efforts help to deepen the understanding of the impacts of meteorological conditions on ACI and further constrain the uncertainties of ACI.

We added the reasons for selecting WRF-Chem-SBM in the third and fourth paragraphs of the Introduction, and provide a detailed description of our design in Section 3.3.

Subsection 3.2, 'Experiment setup', should be moved into the WRF-Chem description or at least earlier in Section 3, preferably before Figure 2.

It has been moved to Section 2 as Subsection 2.2.

If I am understanding correctly, the middle columns in both Figs. 4 and 5 are from the Control experiment. If so, please clarify why the spatial distributions for Nd and CLWP in Fig. 5 differ noticeably from those in Fig. 4 (e.g., an empty area in Fig. 4 but not in Fig. 5, etc.), and why precipitation also exhibits subtle differences. Please ensure consistent sampling/calculation for region maps like these.

Yes, the middle columns in Figures 4 and 5 are both from the Control experiment.

The difference arises because Fig. 4 employs simulated data that is spatio-temporally matched with observational data. The specific procedures are as follows: 1) as stated in the first paragraph of Section 2.3, when evaluating simulation data, interpolation of simulation/observation data was performed following the principle of resolution from high to low. MODIS cloud data (1 km resolution) have a higher spatial resolution than the simulation (2.4 km), while IMERG precipitation data (0.1° resolution) have a lower resolution than the simulation. Therefore, MODIS cloud data were interpolated to the model grid, while simulated precipitation was interpolated to the IMERG grid. 2) As described in the second paragraph of Section 2.3, observational and simulated data were matched for the evaluation.

Specifically, a simulated value at a given grid point and time step was considered valid only if a corresponding valid observational value was available at the same location and time. If no valid observations were available at a grid point throughout the entire study period, that location was left blank in the figure.

The simulated values used in Fig. 4 underwent the above processing steps. This rigorous matching and masking procedure explains the noticeable differences between the data presented in Fig. 4 and the study-period averages shown in Fig. 5. Additionally, since IMERG has a resolution of 1 day, Figure 4 shows the cumulative precipitation from February 2 to 4, while Figure 5 displays the cumulative precipitation for the entire simulation period (from 12:00 on February 1 to 00:00 on February 5). We have noted this in the caption of Figure 4.

When describing figure results, please also list a plain-number expression alongside the scientific expression to help intuitive interpretation. For instance, at L402: 'At sub-moderate supersaturation levels (…)' include the normal expressed percentage values (<10-0.9% → < ~0.12%).

We have added plain-number expressions alongside all scientific expressions.

Please carefully revisit whether the cited supporting figures actually show and support the associated statements. Some cases are included in detail comments below.

We have made revisions based on your specific comments and carefully reviewed and modified the entire manuscript to ensure that cited supporting figures support the associated statements.

Specific Comments

L47. You may want to narrow the statement down to 'satellite observation…' given the reference cited.

Here we aim to express the general limitations of observations, including retrieval uncertainties, instrument errors, and interference from the radiative effects of aerosols and clouds, thereby introducing the need for the integration of simulation models. The original citation only supported uncertainty in satellite retrieval and interference from radiation, which was insufficient. We added a cited statement regarding instrument errors.

L62. Please include a brief description of the following sessions of the manuscript.

We added a brief description of the sections at the end of the first section.

L96. What is the uncertainties of this Nd retrieval compared with the in-situ observation.

The studies evaluated the N_d retrievals against in-situ observation, and found that the N_d retrievals perform well for relatively homogeneous, optically thick and unobscured stratiform clouds under high solar zenith angle conditions (Grosvenor and Wood, 2014; Bennartz and Rausch, 2017; Jia et al., 2021). At very thin cloud, the retrievals suffer from large uncertainties arising from instrument errors and other sources of reflectance error for COT and CER (Zhang and Platnick, 2011; Sourdeval et al., 2016), we thus exclude the data for transparent-cloudy pixels (i.e. COT < 5), as described in Section 2.4.

We added this description in Section 2.3.

L99. Please specify the (approximate) local hour of Terra overpasses over ECO.

It passes over ECO at approximately 03:00 UTC, which corresponds to around 11:00 local time. We have added notes here.

L111. Please specify the matching logic (e.g., whether the WRF output at the nearest time step or an average over surrounding times was used). For a given WRF grid cell, approximately how many MODIS L2 records were averaged?

The matching utilizes the nearest time step of WRF output. During the study period, the number of valid MODIS records varies across grid cells, with the averaged value for each cell corresponding to 0 to 6 records. This description has been added to the fourth paragraph of Section 2.4.

L126. How much uncertainty will these two different modeled Nd derivations introduce into the later ACI analysis? Can you show a comparison of calculated/simulated Nd vs. directly output Nd?

Based on the results of the Control experiment, we present the N_d values derived from both the empirical formula calculation and the direct model output (Fig. R2).

Physically, the model-output N_d is the result of precise calculations from the model's prognostic equations and is highly consistent with meteorological, aerosol, and other cloud properties. In contrast, the N_d calculated using the empirical formula is employed to enable comparison with satellite data on the same basis, but its physical consistency and accuracy are inferior to the model-output values. In terms of overall magnitude, because a relatively loose criterion (CIWC = 0 and CLWC > 0) was adopted for identifying liquid-phase cloud layers in the simulations, many tenuous clouds that would not be detected by satellites were included in the in-cloud mean calculation. Consequently, the model-output N_d is, on average, one order of magnitude lower than that calculated using the empirical formula.

Regarding uncertainty, after dividing the empirically calculated N_d by 10 to offset the systematic numerical difference between the two N_d, the two show similar variations at high COT (Figs. R2a–c). However, for optically thin clouds (COT < 5.0), the empirical formula tends to overestimate N_d, a finding that aligns with the evaluation of satellite N_d retrievals cited in Section 2.3 and is consistent

with the rationale for the MODIS data screening criteria. The use of empirically derived N_d introduces substantial uncertainty into the associated ACI analysis. Specifically, for clouds with $N_d < 1000$ cm^{-3}, this can amplify or reduce ACI signals directly related to N_d by factors ranging from 2 up to more than 10, with the impact increasing as N_d decreases (Fig. R2f, i, and l). Given the large uncertainties introduced by the empirical formula in ACI analysis, the model-output N_d is used for the analyses based on simulation results. We have added this note to the third paragraph of Section 2.4.

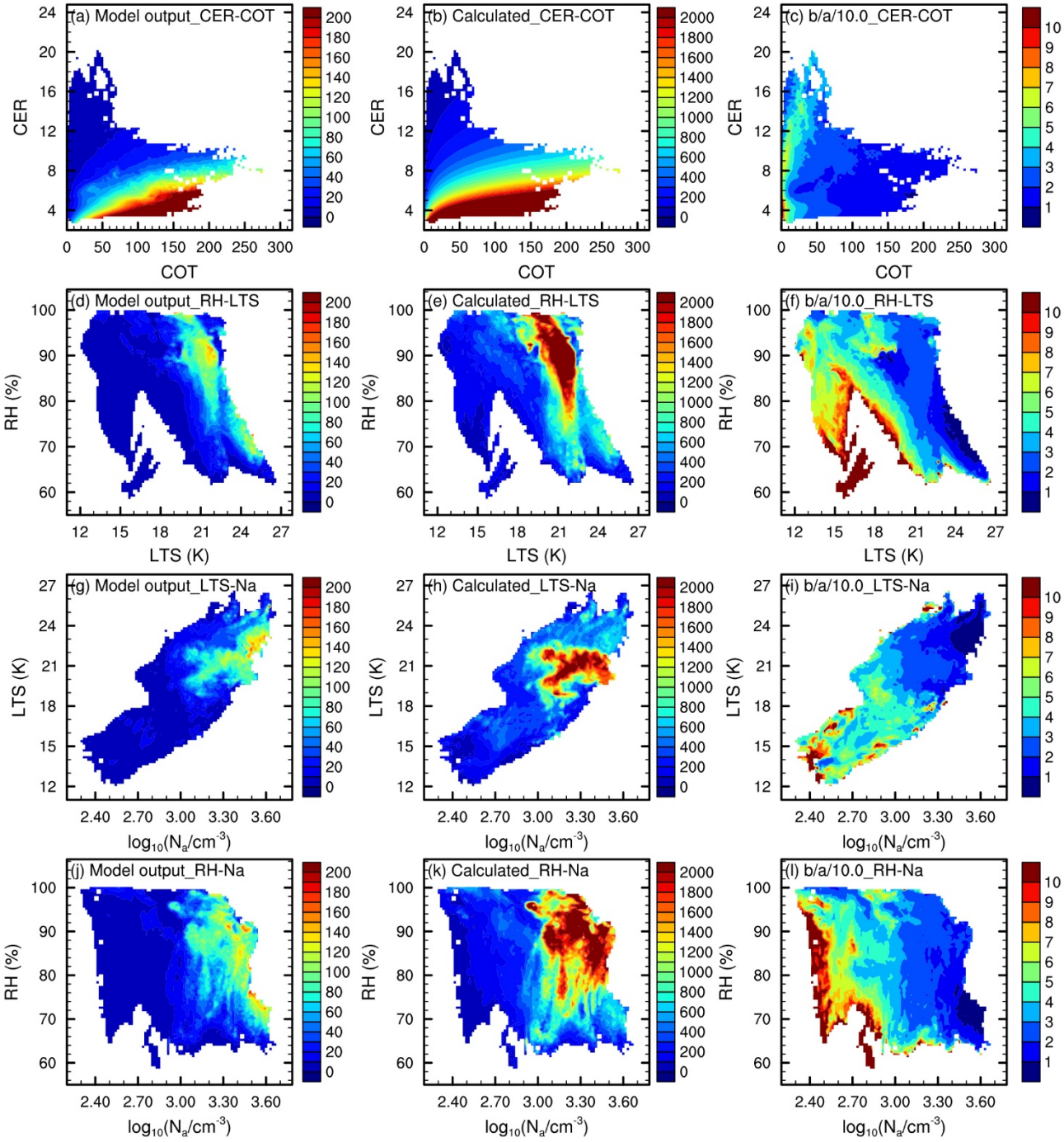

Figure R2. In-cloud mean N_d (Control experiment) derived from direct model output (left column) and empirical formula (Eq. (1) in the main text, middle column), along with the ratio of (b) to (a) divided by 10 (right column), as functions of COT and CER (a–c), LTS and RH (d–f), N_a and LTS (g–i), and N_a and RH (j–l). The data processing method is the same as that used in Fig. 6.

L141. Please specify the lat/lon range of the red box.

The ECO region in this study spans longitudes 123.03–126.24°E and latitudes 30.41–33.14°N. We added this note where we first defined the simulated ECO domain in Section 2.2.

L152. Is there a specific reason for selecting 1300 m? Also, how does the model cloud-top height compare with the satellite CTH?

Since this study focuses on liquid-phase clouds, which typically reside at low altitudes, using column-averaged meteorological variables cannot accurately capture the influence of meteorological fields on ACI. Therefore, we adopted the column-averaged value of the lower atmosphere. The specific choice of 1300 m corresponds to the mean height of the model's 16th layer (counting from the surface upward), as layers 1–16 encompass over 97% of cloud droplets across all experiments. The meteorological conditions within this range are most closely linked to ACI in the liquid-phase clouds studied.

In Section 3.2, we added evaluations of simulated CTH and cloud top temperature (CTT). The simulated and observed CTH show strong correlation (r = 0.83) in spatial distribution. However, due to differences in cloud-top detection methods between the model and MODIS, as well as limitations in the model's ice-phase parameterization (many MODIS liquid-cloud samples exhibit CTT below -30°C, while the simulated liquid clouds have a minimum CTT of -7°C. Under the model's parameterization, only mixed-phase or ice-phase clouds exhibit lower CTT values), the model underestimates CTH by an average of 53.71% compared to MODIS.

L152. Please correct me if I'm wrong, but by eye are LTS and RH exactly the same between the

Control and Clean regimes, or are the differences too subtle to visualize?

We have redrawn Figure 2 so that each subplot presents a comparison between two experiments for a single variable, thereby more clearly illustrating the variations of individual variables between them. As shown in the new Figures 2a and 2b, the LTS and RH from the two experiments exhibit general consistency in both magnitude and temporal evolution. This aligns with our intended outcome; i.e., by assimilating observations and turning off radiative effects, external factors are minimized, thereby ensuring that the differences in ACI between the two experiments arise primarily from the influence of continental aerosols.

At a more detailed level in the new figures, slight discrepancies are observed in the mean values and uncertainty ranges of LTS and RH between the two experiments, which are attributed to feedback from aerosol–cloud interactions on the meteorological fields.

L154. Do the variables shown in Fig. 2 represent domain means or cloud-sample means?

Fig. 2 represents domain means. We have added the note "averaged over ECO" to the figure caption.

L155. This 'dominant-factor transition' statement needs physical-mechanism support. Otherwise, omit it and reframe as a description of wind direction (as in the next sentence), or simply state that the domain was impacted by cold-air advection from the northwest.

We have revised this sentence to the relatively rigorous description "Changes in atmospheric circulation alter the meteorological conditions over ECO, as characterized by variations in LTS." to ensure coherence with the surrounding context.

L162. …inhibiting updraft (Fig. S1i)

Thanks for the reminder. We've added it.

L163. I wouldn't say 'rapid' given the wind speed isn't significantly faster than in the LTS < 17 scenario.

We have changed it to "…due to intense condensation caused by the advection of northwestern low-level cold air…".

L171. 'low-pollution' might be misleading, try 'moderate' or 'relatively low', given that 'clean' is used later.

We have changed it to "relatively low-pollution".

L172. That is an ultraclean condition; I would like to see the corresponding Nd.

We have added N_d to Figure 2 and its corresponding description.

L173. Which case? Are you referring to the polluted or clean case as reflecting typical variations in the joint field over your study region? Please clarify. I recommend retuning this paragraph so the message is tied more tightly to this particular study if you want to keep these general statements.

The term "case" here denotes the ACI across both the Control and Clean experiments during the study period. It captures the clear variations in meteorological conditions, the distinct aerosol changes within each experiment, and the significant aerosol differences between the two simulations—collectively representing typical variations in aerosols and meteorological fields. Our previous statement was not sufficiently clear. We have revised this paragraph to the more precise and contextually relevant

statement “As mentioned above, the shift in meteorological conditions over ECO during the simulation period, the distinct aerosol variations in each experiment, the significant aerosol differences between the two experiments, and the resulting disparities in cloud properties—both within each experiment and between them—collectively provide abundant samples for ACI analysis. This robustly supports the comprehensiveness of the study”.

L211. It looks like the Control has larger error bars (and slightly more outliers) than Control_NoDA, especially for the wind components. I recognize the better correlation in Fig. S2; however, can you quantify mean bias or RMSE between these two and observations to support your statement?

The impact of assimilation on the NMB and RMSE between observations and simulations varies across meteorological elements, with both positive and negative effects observed. These two metrics do not sufficiently support the claim of an "overall positive impact".

We have revised our previous statement regarding the "overall positive impact" based on the vertical profiles in Figure 3, as it lacked rigor. The updated text acknowledges that, from the perspective of statistics at each vertical level, data assimilation improves the simulation of some meteorological elements while also exacerbating model-observation discrepancies in many cases. The overall enhancing effect of assimilation is instead supported by the clearly improved model-observation correlation demonstrated in Figure S3. Additionally, we briefly note here (with a detailed explanation provided in Section 3.3) that assimilation helps maintain meteorological consistency between experiments, to assist in illustrating the necessity of assimilation.

L240. Please also note in the caption that the lower subpanels are for the red-box domain.

We have added the note indicating the domains corresponding to the subpanels in the figure caption.

L297. If you only present counts in Fig. 6m-o, I would not call it ‘occurrence frequency’, which usually meant for depict fraction or percentage. Suggest just use ‘counts’ or ‘samples’. Or maybe you can get the actual fractional frequency of occurrence of clouds.

We have replaced "frequency" with "counts" in the relevant figures and their corresponding descriptions.

L301. Do you have a physical explanation for the increased cloud lifetime at the high-LTS tail (>24 K), which also corresponds to the lowest RH? I wonder if entrainment mixing is inhibited, given that Nd (CER) is comparatively lower (larger) at that tail.

Thank you very much for this comment. We compared the entrainment intensity of the Control

experiment between LTS ≥ 24 K and LTS < 24 K conditions (Fig. R3a), and between the Control and Clean experiments under LTS ≥ 24 K conditions (Fig. R3b) under relatively dry conditions (RH < 80%), to explain the increased cloud lifetime at the high-LTS tail (>24 K). By adapting the methodology of Jia et al. (2019) and refining it based on model outputs, we defined the entrainment intensity as the difference in CLWC between the layers immediately below (non-entrainment zone) and above (entrainment zone) the vertical layer with maximum CLWC in clouds with CLWP > 1 g·m^{-2}, divided by the maximum CLWC (i.e. ($CLWC_{non\text{-}entrainment} - CLWC_{entrainment}$) / $CLWC_{max}$).

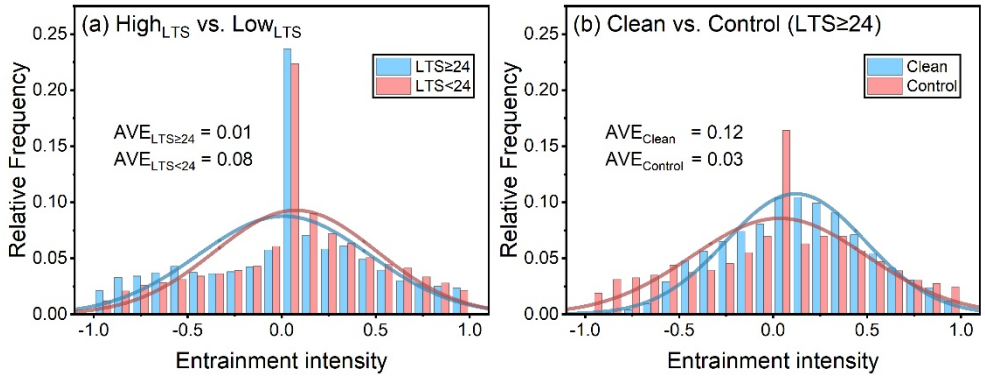

Figure R3. Frequency distribution histograms and fitted curves of entrainment intensity for liquid-cloud samples (CLWP > 1 g·m^{-2}) under relatively dry conditions (RH < 80%), showing comparisons between environments with LTS ⩾ 24 K and LTS < 24 K (a, from Control experiment), and between Control and Clean experiments within the LTS ⩾ 24 K environment (b).The entrainment intensity is defined, following Jia et al. (2019) with refinements based on model outputs, as ($CLWC_{non\text{-}entrainment} - CLWC_{entrainment}$) / $CLWC_{max}$, where the non-entrainment and entrainment zones are the layers immediately below and above the level of maximum CLWC in clouds with CLWP > 1 g·m^{-2}.The histograms are obtained by first assigning liquid-phase cloud samples under different conditions to entrainment intensity intervals according to their corresponding entrainment intensity, and then calculating, for each interval, the relative frequency of samples with respect to the total number of samples. The curves represent fitted distributions of these frequencies to better highlight the differences in entrainment intensity under different conditions.

The results align with your inference: entrainment intensity consistently decrease both in high-LTS environments compared to low-LTS conditions and in Control relative to Clean experiments under high-LTS regimes. This demonstrates that stable atmospheric conditions and enhanced cloud development driven by continental aerosols suppress the weakening of clouds by entrainment, ultimately prolonging cloud lifetime. We have added this analysis at the end of the second paragraph in Section 4.1.

L335. It will not be intuitive to say 'more large droplets,' since the 75th percentile of CER under Control is still largely smaller than under Clean. Consider: 'collision–coalescence at lower levels can produce large droplets.'

We have changed it to "The enhanced vertical development of low-level clouds (below 1500 m), as shown in Figs. 8e-h and S9g-l, strengthens collision-coalescence (producing large droplets)…"

L336. Have you checked cloud fraction and sample size vertically? In the Increase_ scenario, the ~3 km samples appear fewer (narrower spread), so precipitation enhancement may stem from different cloud layers (and not only from 'vertical development of the cloud layer'). If so, please make this clear.

It would help to examine vertical cross-sections of clouds (Nd, CER, Nr, etc.) for both scenarios to confirm. Since Fig. 4 suggests regional clustering for Increase_/Decrease_ samples, a SW–NE slice could work, please consider this.

Since the cumulative precipitation shown in Fig. 5 exhibits an east-west distribution pattern, its zonal variation provides a relatively clear basis for stratified precipitation analysis. We therefore generated vertical cross-sections (Fig. S9) with dimensions of height and longitude, where values at each longitude coordinate represent the mean across all latitudinal grids at that longitude.

From the cross-sections of CLWC and RWC, it is clear that precipitation originates from different cloud layers. We revised this paragraph to "the enhanced vertical development of low-level clouds (below 1500 m) strengthens collision-coalescence (producing large droplets), and, coupled with a substantial increase in droplet numbers in the N_d-limited relatively high-level clouds (above 1500 m), collectively drives the pronounced rise in N_r and RWP across all levels with liquid-phase cloud".

Figure 8. The legends (e.g., Increase/Decrease_CER) are misleading. Consider renaming to clearer identifiers, e.g., CER (increased-precip samples).

We have changed the legends to "…increased/decreased-precip samples".

L364. The correlation is significant but moderate; what message is this intended to convey? Because you did not show the relative vertical position of 950 hPa cold-air advection versus the cloud layers, the physical interplay is not determinate. I guess you can remove this...

We have removed this sentence.

L365. Can you remind me where did you show the Na relationship to LTS? Are you referring to Fig. 9a? And please add the support figure indentifer to this two statements.

Based on the covariation between LTS and N_a in Figure 2 and the circulation changes under different LTS states in Figure 1, we demonstrate the overall consistency between LTS and N_a over ECO during the winter monsoon in the Control experiment. This statement is repeated here to maintain paragraph continuity, but the absence of identifiers and corresponding explanations makes these assertions appear abrupt. And, the discussion here is referring to Column 2 of Fig. 9.

We have revised and added the identifier for the supporting figure in these statements. This paragraph has been moved to the end of the second paragraph in Section 4.2 to enhance the structural clarity of

the description related to Figure 9.

Figure 10. Please clarify the units in panel (a). The in-cloud Na magnitudes in both experiments seem to far exceed the number concentrations shown previously (e.g., Figs. 2, 5). If you are showing an aerosol size distribution, the y-axis should be dN/dlogDp (cm^{-3}).

Also, what is the relationship between activated aerosol Naa and cloud-droplet Nd in the model outputs? Please elaborate.

Thank you for the reminder. We have corrected the data in Figure 10 and changed the figure to size distribution plots with dN/dlogD (cm^{-3}) as the y-axis.

In WRF-Chem-SBM, each cloud droplet corresponds to an activated aerosol particle, meaning N_d and N_{aa} are equivalent in total quantity. Figure 10b shows the spectral distribution of cloud droplets through the variation of N_d across different bins, while Figure 10a displays the activation efficiency of aerosols by comparing N_a and N_{aa} of the four aerosol bins. We have added this explanation to the caption of Figure 10 and included an identifier in the corresponding text.

L369. Fig. 10b provides limited support for this statement (no CLWP/RLWP shown). Please elaborate and/or provide a clear reference.

We have added the reference "(Figs. 9e-f, i-j and q-r)" here.

L377. At least CER and RWP do not increase steadily with RH. Please provide statistical support for 'stronger sensitivity,' e.g., correlations or regression slopes of cloud properties vs. LTS/RH.

We have revised "steadily increasing" to "generally increasing" (as correlations of CER and RWP with RH being 0.46 and 0.67, respectively).

We have added a statistical analysis of correlations between cloud properties and LTS/RH (Table R1) to support the statement of "stronger sensitivity", and revised the corresponding content in the manuscript.

Table R1. Correlations between cloud properties (shown in Fig. 9) and LTS or RH (correlations are calculated after averaging cloud property values across all N_a coordinates for each corresponding LTS or RH value).

Property	RH				LTS			
	Clean		Polluted		Clean		Polluted	
	r	p	r	p	r	p	r	p
CER	0.46	<0.01	0.96	<0.01	0.86	<0.01	0.15	0.13
CLWP	0.81	<0.01	0.75	<0.01	-0.54	<0.01	-0.34	<0.01

RWP	0.67	<0.01	-0.14	0.16	0.18	0.07	-0.50	<0.01
$\log_{10}(N_d/N_a)$	0.59	<0.01	0.89	<0.01	-0.33	<0.01	0.28	<0.01
$\log_{10}(CLWP/N_a)$	0.58	<0.01	0.70	<0.01	-0.14	0.18	-0.82	<0.01
$\log_{10}(RWP/N_a)$	0.65	<0.01	0.70	<0.01	0.22	0.03	-0.36	<0.01

L379. Please elaborate. If activation ratio, CLWP, and RWP largely increase with Na across RH ranges, how is 'greater sensitivity' exhibited?

We have used the correlations presented in Table S1 to demonstrate that under the polluted regime, CER, N_d/N_a, $CLWP/N_a$, and RWP/N_a all exhibit higher sensitivity to RH (on average over 46.98% higher) compared to the clean regime. This contrasts with the behavior of CLWP and RWP, which show slightly and significantly lower sensitivity to RH, respectively, than under the clean regime, due to interference from their dependence on N_a caused by these collision-coalescence-dominated cloud properties.

We have revised the statement in this section (the third paragraph of Section 4.2) based on the statistics.

L380. Regarding the 'manner' of cloud vs. Na being similar to high LTS (I presume Fig. 9b, 9f, etc.): would that mean cloud properties are largely impacted by aerosol loading rather than environmental parameters? If so, what 'dominated role' is cold-air advection playing? You have not established a strong physical relationship between cold advection and cloud (a correlation between column-mean Na and 950 hPa temperature is not enough). If you want to discuss the physical role of cold advection, at least show the vertical dependence of cloud properties on it. Please elaborate and provide figure support.

Regarding the comment on "mean cloud properties are largely impacted by aerosol loading rather than environmental parameters", we acknowledge that the results in Figure 9 do show a significant influence of N_a on cloud properties, with the rate of change in cloud properties with respect to N_a often exceeding that with respect to meteorological factors in many conditions. Our original intention was to use the broadly consistent variation of cloud properties with N_a across both RH and high-LTS perspectives to illustrate the dominant role of cold-air advection associated with high LTS in ACI under winter monsoon background. However, we recognize that this variation is substantially influenced by N_a, making our previous assertion of a "dominated role" insufficiently rigorous. Accordingly, the statement has been revised to summarize the regulatory role of meteorological fields on ACI, as demonstrated in Figure 9. Specifically, the shift from convection-dominated regimes at low LTS to cold advection-dominated regimes at high LTS modulates the qualitative impact of aerosols on cloud properties under polluted conditions, while the level of RH governs the quantitative effect of aerosols on cloud development.

Regarding the physical relationship between cold advection and clouds, Section 3.1 demonstrates the synchrony among high LTS, strong cold advection, and high N_a in the Control experiment through atmospheric circulation and N_a variations corresponding to different LTS levels. Section 4.1 further illustrates the association of cloud development in the Control experiment and the enhancement effect of continental aerosols on clouds with cold advection through cloud property variations with LTS. This association exists only in the Control experiment. In the Clean experiment, which lacks continental aerosols, high values of N_d and CLWP instead mainly appear under low LTS.

Furthermore, our argument in Section 4.1 regarding the dominant role of cold advection was also insufficiently rigorous, and we have revised it to "In the Clean experiment, high N_d and CLWP occur more frequently in low-LTS environments dominated by updrafts, compared to high-LTS conditions. In contrast, the Control experiment shows a significantly higher frequency of high N_d and CLWP under high-LTS conditions, resulting from the combined effects of substantial continental aerosol transport associated with winter monsoon and strong condensation, as described in Section 3.1".

L392. The RWP sharply decrease with Na (> 10-0.4) under low supersaturation, which reflects the precip suppression effect of aerosol, please spell it out.

We have changed this sentence to "When N_a exceeds $10^{-0.4}$ (~0.40) cm^{-3}, further increases in N_a under low supersaturation cause CER to rapidly decrease to around 15 μm, thus suppressing precipitation, while high RWP appears only under high supersaturation".

L406. ~0.16% supersaturation is not necessarily 'high' condition.

Due to the substantial depletion of supersaturation by aerosols, although this supersaturation is not high in absolute terms, it represents a relatively high value among all Control samples. We have attached this note to the text and changed "high supersaturation" to "relatively high supersaturation".

L407. ~0.01% supersaturation is fairly low, again, describing the supersature with a normal expression of number will give the reader more sense.

We have revised this to "relatively moderate supersaturation" and provided normal expressions alongside these scientific expressions.

L410. As above, please further explain the physical basis for cold-advection dominance. This statement is somewhat misleading: updraft strength has limited direct relationship to aerosol concentrations. Please specify which cloud process is dominated by updraft under low-aerosol conditions and how that dominance is dampened under high-aerosol conditions. In which experiment would cold-advection effects be more effective?

Yes, updraft strength cannot be directly attributed to aerosol concentrations. Our intended argument was based on the co-variation between LTS and N_a over ECO under winter monsoon background, as described in Section 3.1. Specifically, lower N_a generally corresponds to lower LTS, where cloud processes are dominated by updrafts, while higher N_a is associated with higher LTS, a regime in which updrafts are suppressed and cloud processes are governed by cold-air advection. However, our initial statement was somewhat ambiguous in conveying this reasoning. To clarify, we have revised the relevant paragraph to repeat the pattern of the Control experiment presented in Section 3.1: increasing LTS is accompanied by rising N_a, weakening updrafts, and strengthening cold-air advection. This interpretation is further supported by the decrease in temperature advection and vertical wind speed with increasing N_a in the Control experiment, as shown in Figure R4.

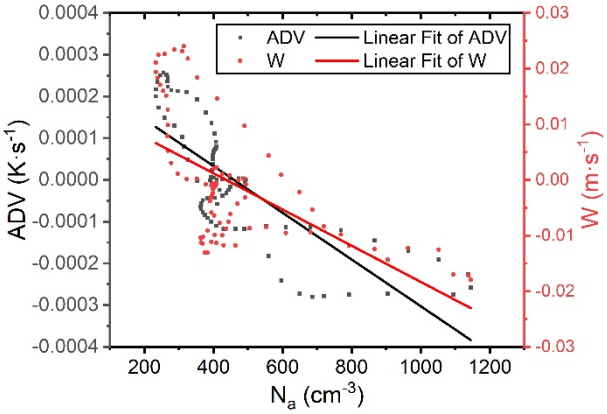

Figure R4. Variations of vertically weighted mean temperature advection (ADV, calculated as $-\left(U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}\right)$) and vertical wind velocity (W) from the near-surface to 1300 m with column-averaged N_a over ECO (the value in the figure represents the ECO average).

The significant impact of the synchronous intensification of cold advection and N_a on ACI is only evident in the control experiment corresponding to the polluted regime. In the clean experiments without continental aerosols, the variation in N_a shows no clear correlation with cold advection. We have revised this paragraph based on the comment.

L411. Provide statistical evidence or figure support for "At moderate Na, both updrafts and cold advection are weak…"

We have added statistical support for it (Fig. S10) and revised the sentence to "moderate N_a environments experience neither sufficiently strong cold advection nor sustained updrafts (as the average variations of temperature advection and vertical wind speed with N_a in ECO, shown in Fig. S10)".

L449. You may wish to point out that the extensions of cloud lifetime (actually cloud frequency in this study; Fig. 6) at low and high LTS arise from different physical reasons: low LTS/vigorous updrafts

invigorate frequent cloud hydrometeors, whereas high LTS/stronger subsidence maintains the cloud layer.

Many thanks for this comment. We have revised the conclusion and the corresponding statement in the second paragraph of Section 4.1. For example, the sentence in the conclusion has been changed to "Continental aerosols extend cloud lifetime (actually cloud sample counts in this study) in moist environments, with this enhancement strongest under low and high LTS conditions, corresponding to vigorous updrafts (invigorating frequent cloud hydrometeors) and strong cold advection (causing intense condensation and maintaining cloud), respectively".

L482. I would like to see a revised Conclusions section after you address the main-text comments.

We have revised the conclusion.

References

Ahmadov, R.: WRF-Chem: Online vs Offline Atmospheric Chemistry Modeling, ASP Colloquium; National Center for Atmospheric Research (NCAR): Boulder, CO, USA, https://edec.ucar.edu/sites/default/files/2022-02/1_Ahmadov_07_29_2016.pdf, 2016.

Andrejczuk, M., Gadian, A., and Blyth, A.: Numerical simulations of stratocumulus cloud response to aerosol perturbation, Atmos. Res., 140-141, 76-84, https://doi.org/10.1016/j.atmosres.2014.01.006, 2014.

Bennartz, R., Fan, J., Rausch, J., Leung, L. R., and Heidinger, A. K.: Pollution from China increases cloud droplet number, suppresses rain over the East China Sea, Geophys. Res. Lett., 38, https://doi.org/10.1029/2011GL047235, 2011.

Bennartz, R. and Rausch, J.: Global and regional estimates of warm cloud droplet number concentration based on 13 years of AQUA-MODIS observations, Atmos. Chem. Phys., 17, 9815-9836, https://doi.org/10.5194/acp-17-9815-2017, 2017.

Briant, R., Tuccella, P., Deroubaix, A., Khvorostyanov, D., Menut, L., Mailler, S., and Turquety, S.: Aerosol–radiation interaction modelling using online coupling between the WRF 3.7.1 meteorological model and the CHIMERE 2016 chemistry-transport model, through the OASIS3-MCT coupler, Geosci. Model Dev., 10, 927-944, https://doi.org/10.5194/gmd-10-927-2017, 2017.

George, C., Ammann, M., D'Anna, B., Donaldson, D. J., and Nizkorodov, S. A.: Heterogeneous photochemistry in the atmosphere, Chem Rev, 115, 4218-4258, https://doi.org/10.1021/cr500648z, 2015.

Grosvenor, D. P. and Wood, R.: The effect of solar zenith angle on MODIS cloud optical and microphysical retrievals within marine liquid water clouds, Atmos. Chem. Phys., 14, 7291-7321, https://doi.org/10.5194/acp-14-7291-2014, 2014.

Guo, J., Luo, Y., Yang, J., Furtado, K., and Lei, H.: Effects of anthropogenic and sea salt aerosols on a heavy rainfall event during the early-summer rainy season over coastal Southern China, Atmos. Res., 265, 105923, https://doi.org/10.1016/j.atmosres.2021.105923, 2022.

Haghighatnasab, M., Kretzschmar, J., Block, K., and Quaas, J.: Impact of Holuhraun volcano aerosols on clouds in cloud-system-resolving simulations, Atmos. Chem. Phys., 22, 8457-8472, https://doi.org/10.5194/acp-22-8457-2022, 2022.

Heikenfeld, M., White, B., Labbouz, L., and Stier, P.: Aerosol effects on deep convection: the propagation of aerosol perturbations through convective cloud microphysics, Atmos. Chem. Phys., 19, 2601-2627, https://doi.org/10.5194/acp-19-2601-2019, 2019.

Hodzic, A., Mahowald, N., Dawson, M., Johnson, J., Bernardet, L., Bosler, P. A., Fast, J. D., Fierce, L., Liu, X., Ma, P.-L., Murphy, B., Riemer, N., and Schulz, M.: Generalized Aerosol/Chemistry Interface (GIANT): A Community Effort to Advance Collaborative Science across Weather and Climate Models, Bull. Am. Meteorol. Soc., 104, E2065-E2080, https://doi.org/https://doi.org/10.1175/BAMS-D-23-0013.1, 2023.

Jia, H. L., Ma, X. Y., and Liu, Y. G.: Exploring aerosol-cloud interaction using VOCALS-REx aircraft measurements, Atmos. Chem. Phys., 19, 7955-7971, https://doi.org/10.5194/acp-19-7955-2019, 2019.

Jia, H. L., Ma, X. Y., Yu, F. Q., and Quaas, J.: Significant underestimation of radiative forcing by aerosol-cloud interactions derived from satellite-based methods, Nat. Commun., 12, https://doi.org/10.1038/s41467-021-23888-1, 2021.

Jiang, M., Li, Y., Hu, W., Yang, Y., Brasseur, G., and Zhao, X.: Model-based insights into aerosol perturbation on pristine continental convective precipitation, Atmos. Chem. Phys., 23, 4545-4557, https://doi.org/10.5194/acp-23-4545-2023, 2023.

Liu, Z., Ming, Y., Zhao, C., Lau, N. C., Guo, J., Bollasina, M., and Yim, S. H. L.: Contribution of local and remote anthropogenic aerosols to a record-breaking torrential rainfall event in Guangdong Province, China, Atmos. Chem. Phys., 20, 223-241, https://doi.org/10.5194/acp-20-223-2020, 2020.

Khain, A. P., Beheng, K. D., Heymsfield, A., Korolev, A., Krichak, S. O., Levin, Z., Pinsky, M., Phillips, V., Prabhakaran, T., Teller, A., van den Heever, S. C., and Yano, J. I.: Representation of microphysical processes in cloud-resolving models: Spectral (bin) microphysics versus bulk parameterization, Rev. Geophys., 53, 247-322, https://doi.org/10.1002/2014rg000468, 2015.

Liu, Y., Lin, T., Zhang, J., Wang, F., Huang, Y., Wu, X., Ye, H., Zhang, G., Cao, X., and de Leeuw, G.: Opposite effects of aerosols and meteorological parameters on warm clouds in two contrasting regions over eastern China, Atmos. Chem. Phys., 24, 4651-4673, https://doi.org/10.5194/acp-24-4651-2024, 2024.

Prabhakaran, P., Hoffmann, F., and Feingold, G.: Evaluation of Pulse Aerosol Forcing on Marine Stratocumulus Clouds in the Context of Marine Cloud Brightening, J. Atmos. Sci., 80, 1585-1604, https://doi.org/10.1175/JAS-D-22-0207.1, 2023.

Reutter, P., Su, H., Trentmann, J., Simmel, M., Rose, D., Gunthe, S. S., Wernli, H., Andreae, M. O., and Pöschl, U.: Aerosol- and updraft-limited regimes of cloud droplet formation: influence of particle number, size and hygroscopicity on the activation of cloud condensation nuclei (CCN), Atmos. Chem. Phys., 9, 7067-7080, https://doi.org/10.5194/acp-9-7067-2009, 2009.

Saleeby, S. M., Berg, W., van den Heever, S., and L’ Ecuyer, T.: Impact of Cloud-Nucleating Aerosols in Cloud-Resolving Model Simulations of Warm-Rain Precipitation in the East China Sea, J. Atmos. Sci., 67, 3916-3930, https://doi.org/10.1175/2010JAS3528.1, 2010.

Sourdeval, O., C.-Labonnote, L., Baran, A. J., Mülmenstädt, J., and Brogniez, G.: A methodology for simultaneous retrieval of ice and liquid water cloud properties. Part 2: Near-global retrievals and evaluation against A-Train products, Q. J. R. Meteorolog. Soc., 142, 3063-3081, https://doi.org/https://doi.org/10.1002/qj.2889, 2016.

Tang, S., Wang, H., Li, X. Y., Chen, J., Sorooshian, A., Zeng, X., Crosbie, E., Thornhill, K. L., Ziemba, L. D., and Voigt, C.: Understanding aerosol‐cloud interactions using a single-column model for a cold-air outbreak case during the ACTIVATE campaign, Atmos. Chem. Phys., 24, 10073-10092, https://doi.org/10.5194/acp-24-10073-2024, 2024.

Zhang, Z. and Platnick, S.: An assessment of differences between cloud effective particle radius retrievals for marine water clouds from three MODIS spectral bands, J. Geophys. Res.: Atmos., 116, https://doi.org/https://doi.org/10.1029/2011JD016216, 2011.