Responses to Anonymous Referee #1

This study investigates the role of aerosol–cloud–radiation interactions in modulating summertime quasi-biweekly rainfall intensity over South China based on both reanalysis data and model simulations, with interesting results provided. Personally, I would like to suggest its acceptance for publication with minor revisions.

Response:

We sincerely appreciate your encouraging and constructive comments, which have greatly helped us improve the quality of this study. We also learned a great deal from your suggestions, which provided us with valuable insights into this field. All of your comments have been carefully addressed and the corresponding revisions have been incorporated into the manuscript. Our detailed, point-by-point responses are provided below (in blue).

Specific comments:

1. Line 31-33, Recent review studies regarding the aerosol effect on clouds and precipitation could be referred and mentioned, Zhao et al. (2023, doi: 10.1016/j.atmosres.2023.106899) and Li et al. (2019, doi: 10.1029/2019JD030758).

Response:

We thank the reviewer for recommending these valuable works, which provide robust insights into aerosol effects on clouds and precipitation. We have carefully studied them and incorporated the relevant findings into the revised Introduction. Please refer to Lines 33–36 in the revised manuscript, as shown below for convenience.

- Lines 33–36: "Aerosols influence clouds and precipitation through two primary mechanisms: one involves directly modifying radiation, while the other acts through their role as cloud condensation nuclei (CCN) or ice nuclei (IN) (e.g., Koren et al., 2004; Tao et al., 2012; Li et al., 2016, 2019; Zhu et al., 2022; Zhao et al., 2023; Stier et al., 2024)."

2. Line 35-36, Not always suppressing precipitation, it sometimes enhances precipitation, as indicated by recent studies.

Response:

Thank you for this insightful comment. In the revised manuscript, we have modified the description to highlight that aerosol radiative effects can lead not only to suppression but also to enhancement of precipitation, depending on environmental conditions. Please refer to Lines 37–41, as shown below for convenience.

- Lines 37–41: "The radiative effect involves the scattering and absorption of solar radiation by aerosols (i.e., the so-called "direct effect"), which commonly leads to atmospheric heating, surface cooling, stabilization of atmospheric stratification, and suppression of precipitation (Bollasina et al., 2011), but can also enhance local or remote precipitation under favorable conditions (e.g., Fan et al., 2015; Zhu et al., 2022; Wei et al., 2023)."

3. Line 37-39, The semi-direct effect often refers the case absorbing aerosols within clouds.

Response:

We thank the reviewer for pointing out this important detail regarding the vertical location of absorbing aerosols. In the revised manuscript, we have added this key information to clarify the definition of the semi-direct effect. Please see Lines 41–43, shown below for convenience.

- Lines 41–43: "In particular, absorbing aerosols within clouds enhance cloud evaporation, thereby inhibiting cloud and precipitation formation, a phenomenon referred to as the semi-direct effect (Ackerman et al., 2000)."

4. Line 42-43, Actually, there are proposed mechanisms for this invigoration phenomenon, while debates exist.

Response:

We thank the reviewer for this important comment. Indeed, the invigoration effect has been widely studied, with several mechanisms proposed — for example, freezing-induced invigoration (Rosenfeld et al., 2008) and condensational invigoration (Fan et al., 2018). At the same time, its occurrence and significance remain debated across different cloud regimes and environmental conditions. To reasonably introduce our research purpose, we have revised the text to explicitly note both the proposed mechanisms and the ongoing debates. Please see Lines 46–48 in the revised manuscript, shown below for convenience.

- Lines 46–48: "Additionally, the aerosols can invigorate deep convective cloud through freezing-induced intensification (Rosenfeld et al., 2008) and enhanced condensational heating (Fan et al., 2018), the so-called invigoration effect (Fan et al., 2025), though its significance remains debated qualitatively and quantitatively."

5. Line 66-68, If possible, a short review about the existing studies over South China is appreciated.

Response:

Thank you for this helpful suggestion. In South China, previous studies on aerosol–precipitation interactions have largely focused on the start and peak times of diurnal precipitation (Guo et al., 2016; Lee et al., 2016; Sun and Zhao, 2021), mesoscale rainfall intensity variations (Zhang et al., 2020; Xiao et al., 2023a), synoptic-scale rainfall variability (Liu et al., 2020; Guo et al., 2022), and seasonal-to-climatological rainfall changes (Wang et al., 2011; Yang and Li, 2014; Zhu et al., 2023). To better introduce the purpose of our study, we have reorganized the last paragraph of the Introduction and added these discussions. Please see Lines 72–80 in the revised manuscript, as shown below for convenience.

- Lines 72–80: "Influenced by active intraseasonal oscillations, persistent heavy precipitation frequently strikes densely populated southeastern China (Hsu et al., 2016), posing increasingly severe threats to socioeconomic development and the livelihoods of billions. Research on aerosol–precipitation interactions over South China in summer has predominantly examined diurnal precipitation shifts (Guo et al., 2016; Lee et al., 2016; Sun and Zhao, 2021), mesoscale rainfall intensity (Zhang et al., 2020; Xiao et al., 2023a), synoptic-scale rainfall variability (Liu et al., 2020; Guo et al., 2022), and seasonal-to-climatological rainfall changes (Wang et al., 2011; Yang and Li, 2014; Zhu et al., 2023). However, despite the importance of intraseasonal oscillations in regulating regional rainfall, few studies have examined aerosol impacts on intraseasonal variability of rainfall intensity."

6. Line 87, Why do not use the radiation from CERES?

Response:

Indeed, the Clouds and the Earth's Radiant Energy System (CERES) provides high-quality Earth radiation budget data. Following this useful suggestion, we collected initial and adjusted radiative fluxes from CERES Synoptic products (abbreviated as CERES-SYN-I and CERES-SYN-A) and compared them with MERRA-2 (Fig. A1). The atmospheric radiative effects associated with intraseasonal rainfall events show highly consistent temporal evolution and magnitudes between the two datasets (Fig. A1a–b). Moreover, the aerosol impacts on the cloud-radiative processes are similar (Fig. A1c). However, CERES-SYN products lack some key parameters: CERES-SYN-I does not provide downward top-of-atmosphere shortwave flux, preventing net shortwave calculations, while CERES-SYN-A omits the pristine-sky condition needed to isolate aerosol effects. For this reason, we used MERRA-2 in the main analysis.

In the revised manuscript, we clarified our rationale for using MERRA-2 (Lines 100–101) and added a supplementary comparison with CERES to demonstrate the robustness of our conclusions (Lines 105–108 and 373). The relevant text is provided below for convenience.

- Lines 100–101: "MERRA-2 provides the complete set of variables required for atmospheric radiation and moisture budget quantifications, whereas other reanalyses and observations lack some of these key variables."

- Lines 105–108: “To further reduce uncertainties inherent in reanalyses, we also employed radiative fluxes from Clouds and the Earth’s Radiant Energy System Synoptic products (CERES-SYN; Rutan et al., 2015) at 1° resolution, and AOD from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 Level-3 aerosol product onboard the Terra satellite (Levy et al., 2013) at 1° resolution.”

- Line 373: “This behavior is consistent with estimates from CERES-SYN (Fig. S4).”

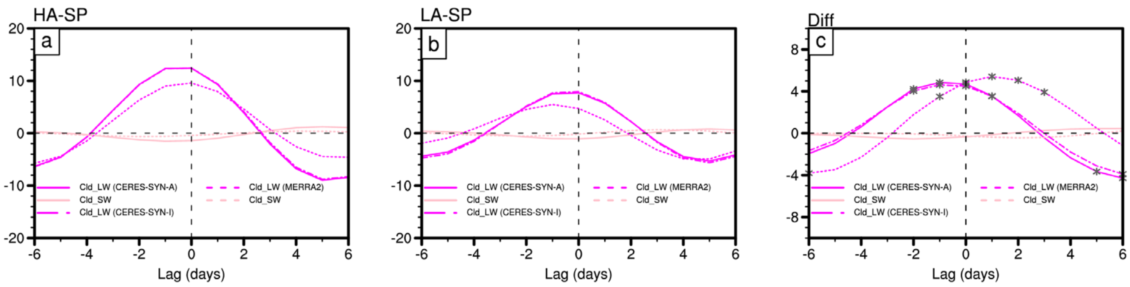

Figure A1. (a) Composite evolution of 8–30-day longwave and shortwave cloud radiative effects (Cld_LW, magenta curve; Cld_SW, pink curve; W m^{-2}) calculated from Eq. (2), derived from CERES-SYN-A (solid curves), CERES-SYN-I data (dash-dotted curves), and MERRA-2 (dashed curves), associated with High AOD–Strong Precipitation (HA–SP) events. Day 0 denotes the peak of rainfall events, while negative and positive values on the *x*-axis indicate days before and after the peak, respectively. (b) and (c) are similar to (a), but represent the composite results for Low AOD–Strong Precipitation (LA–SP) events and the differences between HA–SP and LA–SP events, respectively. In panel (c), the periods when their differences with statistically significant differences at the 90% confidence level are marked by gray asterisks.

7. Line 93-96, Similarly, why do not use CloudSat/Calipso observations?

Response:

We appreciate this constructive suggestion. CloudSat provides high-quality cloud water products, but large temporal gaps prevent its use for analyzing continuous sequences of aerosol–cloud–precipitation interactions at intraseasonal timescales. For this reason, we used reanalyses (MERRA-2 and ERA5) to examine vertical cloud water structures. To ensure their reliability, we compared reanalysis cloud water content profiles with CloudSat 2B-CWC-RO products (Austin et al., 2009). Because of known uncertainties in Cloud Profiling Radar (CPR) retrievals within ~0.5–0.7 km above the surface (Stephens et al., 2008), we excluded CloudSat data below ~0.7 km from the comparison (Zhang et al., 2015). As shown in Fig. A2, ERA5, MERRA-2, and CloudSat capture similar vertical distributions of liquid and ice cloud water content over South China, with ice peaking in the upper troposphere and liquid showing two maxima at middle and lower levels. These features are similar to previous CloudSat-based studies in this region (Yang and Wang, 2012; Zhang et al., 2015), supporting the use of reanalyses in our study.

In the revised manuscript, we clarified this rationale in Lines 113–116, as shown below.

- Lines 113–116: "Although CloudSat provides three-dimensional cloud products (Austin et al., 2009), substantial temporal gaps prevent its use for analyzing continuous sequences of aerosol–cloud–precipitation interactions at intraseasonal timescales. Thus, three-dimensional liquid and ice cloud water contents were instead taken from MERRA-2 and ERA5 to evaluate vertical cloud structures."

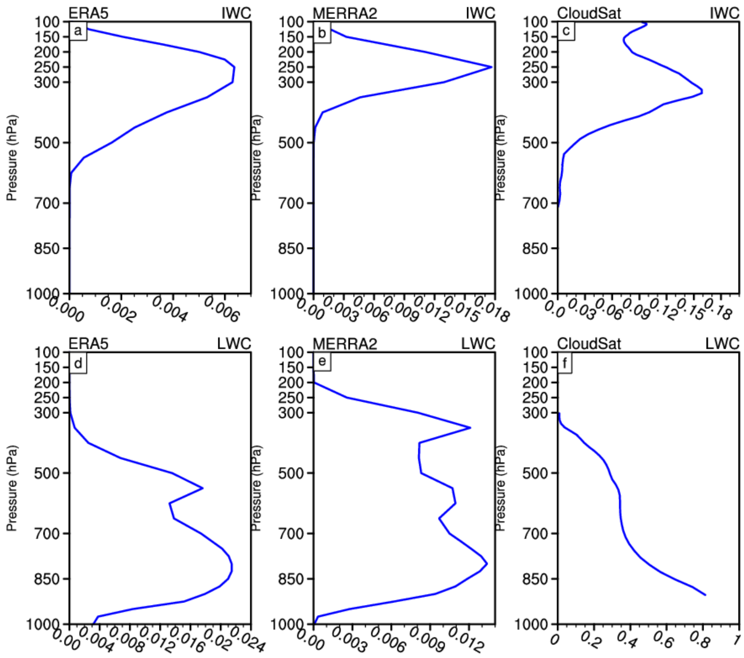

Figure A2. Vertical profiles of mean (a–c) ice cloud water content and (d–f) liquid cloud water content from (a, d) ERA5, (b, e) MERRA-2, and (c, f) CloudSat over South China during boreal summer (May–September) 2006–2020. Units: g m^{-3}

8. Line 134-136, To be fair, limitations for model studies should also be acknowledged.

Response:

We thank the reviewer for this important suggestion. Indeed, while WRF-Chem simulation is a valuable tool to disentangle causal links between aerosols, clouds, and precipitation, they inevitably involve uncertainties, particularly related to the choice of physical parameterizations, emission inventories, and initial and boundary conditions. We have briefly acknowledged these limitations in Section 2.3 (Lines 154–157), and further discussed them in Section 4 when presenting the model results. The revised text is provided below.

- Lines 154–157: "To address this, we conducted a series of experiments using the WRF-Chem version 4.2.2 (Grell et al., 2005; Fast et al., 2006) to support the observed mechanisms responsible for aerosol impacts on clouds and precipitation, although uncertainties remain due to the dependence on emission inventories, physical parameterizations, and initial and boundary conditions."

9. Line 144-145, Could this nudging reduce/remote some effects from aerosol-meteorology interactions? And what will this affect the analysis results?

Response:

Thank you for raising this important point. In our experiments, grid nudging was applied only during the spin-up period to better initialize meteorology, while aerosol–meteorology interactions were analyzed during the subsequent free-running period. This design ensures that nudging does not interfere with the main analysis. We recognize that nudging can partially suppress aerosol impacts on model dynamics (He et al., 2017), so we performed a sensitivity experiment without nudging. The results show consistent aerosol-induced precipitation enhancement (Fig. A3a), confirming that our conclusions are not sensitive to the nudging procedure.

In the revised manuscript, we clarified the nudging setup and discussed its potential impacts on our conclusions (Lines 166–170), as provided below.

➢ Lines 166–170: "To better reproduce the observed circulation and aerosol pattern, grid analysis nudging is applied only during the spin-up period (Abida et al., 2022), allowing meteorological fields to freely interact with aerosols during the analysis period. While nudging could potentially constrain aerosol feedbacks (He et al., 2017), our sensitivity tests confirm that it does not affect the main conclusions (figure not shown)."

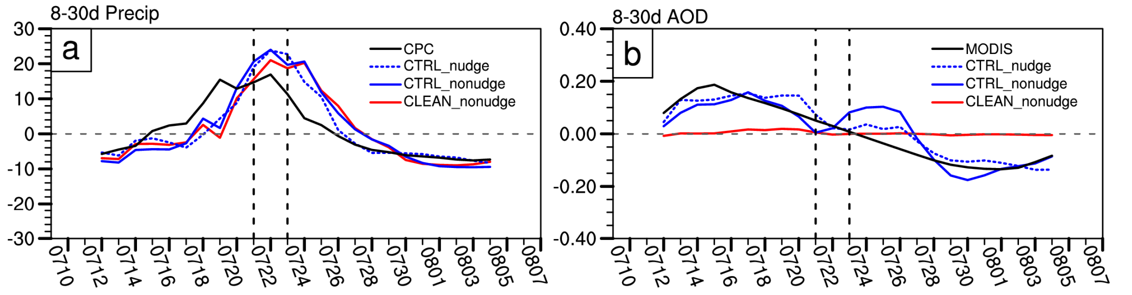

Figure A3. (a) Evolution of precipitation (mm d^{-1}) and (b) AOD (unitless) anomalies averaged over the Pearl River Delta (21°–24°N, 111°–116°E) in the observations (black curves, CPC rainfall and MODIS AOD data), CTRL (blue solid curves) and CLEAN (red solid curves) of no-nudging simulations, as well as CTRL experiment of nudging simulation (blue dashed curves). All simulations are initialized on 9 July 2015.

10. Line 168-170, Why do the authors use so long time as spin-up, instead of 12 or 24 hours as used by many studies?

Response:

We thank the reviewer for this insightful question. In this study, a longer spin-up period was chosen to ensure that locally emitted aerosols became sufficiently mixed and reached a quasi-equilibrated distribution before the analysis period, consistent with earlier WRF-Chem applications to aerosol–meteorology interactions (e.g., Zhu et al., 2022; Wei et al., 2023; Agarwal et al., 2024). To test sensitivity, we performed ensemble simulations with spin-up times ranging from 1 to 6 days, including a 24-hour spin-up. The ensemble results show consistent aerosol-induced precipitation responses, with small ensemble-mean uncertainties, indicating that our conclusions are not sensitive to the choice of spin-up length.

We also recognize that long integrations may accumulate model biases. To minimize this potential impact, grid nudging was applied during the spin-up period, which helps constrain large-scale circulation and reduce drift.

In the revised manuscript, we clarified the rationale for using a multi-day spin-up (Lines 196–199). Please see below for your convenience.

- Lines 196–199: "To allow locally emitted aerosols to become sufficiently mixed and reach a quasi-equilibrated distribution, we adopted spin-up times of 1–6 days, consistent with previous studies (e.g., Zhu et al., 2022). The first few days of each run (4–9 July) are discarded, and the analysis focuses on 10 July–6 August 2015."

11. Line 235-236, One more 50-year observation based climatological study by Su et al. (2020, doi: 10.3390/atmos11030303) is worthy to refer here.

Response:

We apologize for overlooking this important reference and thank you for bringing it to our attention. After reading it, we have cited this paper in Lines 262–265. For your convenience, the details are provided below.

- Lines 262–265: "This behavior aligns with previous studies at the synoptic and decadal timescales (Wang et al., 2011; Yang et al., 2018; Su et al., 2020; Shao et al., 2022; Xiao et al., 2023b), which emphasize that the aerosols tend to suppress light rainfall while enhancing heavy convective precipitation."

12. Line 316, cloud ice particles.

Response:

Thank you for pointing this out. The term has been corrected to "cloud ice particles" in the revised manuscript (Line 358).

13. Line 380, I am not sure if we can use "verification" or not since these are not

observations, but model simulations, while we could say "support".

Response:

We agree with the reviewer that "support" is a more precise term in this context, since the results are based on model simulations rather than direct observations. Accordingly, we have replaced "verification" with "support" in the revised manuscript (Line 429).

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