Responses to Referee #1

This manuscript investigates the critical role of externally transported aerosols over Mount Qomolangma (MQ) in modulating ice-phase cloud formation, downstream precipitation, and regional thermodynamic feedbacks. The topic is of great scientific significance for understanding aerosol–cloud–precipitation interactions over the Tibetan Plateau (TP). However, several key physical mechanisms, theoretical foundations, and feedback loops require further elaboration and clarification before publication. The specific comments are integrated as follows:

1、The study states that aerosols can promote the formation of ice-phase clouds. It is recommended to supplement relevant previous studies to strengthen the theoretical and observational evidence supporting the linkage between aerosols and ice clouds.

Response 1： Thanks for the reviewer's suggestions. We have accordingly added the following discussions in the revised manuscript:

Lines 93-108: Aerosols acting as CCN and INPs may alter cloud droplet activation, promote heterogeneous ice nucleation, and modify the partitioning among liquid, supercooled-liquid, mixed-phase, and ice-phase clouds (Zhu et al., 2024). A small subset of atmospheric aerosol particles can act as INPs and initiate heterogeneous ice formation in ice-phase clouds through immersion, deposition, contact, or condensation freezing. Mineral dust and soot particles are regarded as the primary atmospheric INP types. Once primary ice crystals are generated, depositional growth, riming, the Wegener-Bergeron-Findeisen process (Wegener, 1911; Bergeron, 1935; Findeisen, 1938), and secondary ice production can further amplify cloud glaciation and modify the partitioning between liquid and ice water (Murray et al., 2012). Nevertheless, aerosol concentration alone does not directly represent INP abundance, and the observed aerosol–ice-cloud relationship may also be affected by temperature, humidity, vertical motion, and cloud dynamics (Zhu et al., 2024; Xu et al. 2025). Atmospheric aerosols interact with clouds through tightly coupled microphysical, radiative, thermodynamic, and dynamical processes. Vertical motion, moisture availability, temperature and large-scale circulation are meteorological factors that collectively determine whether elevated aerosol loading stimulates or inhibits cloud and precipitation development. Therefore, the ice-phase clouds could be interpreted as the combined result of aerosol-mediated ice nucleation and favorable thermodynamic and dynamical conditions, rather than as an aerosol effect alone. These interactions are highly nonlinear and depend strongly on cloud type, cloud evolutionary stage, and the surrounding meteorological environment（IPCC, 2023）.

References

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2、This study concludes that under different large-scale atmospheric circulation regimes, ice-phase cloud activated over MQ can be efficiently transported downstream through distinct pathways, exerting a pronounced ice crystal seeding effect on cloud–precipitation conversion. The physical mechanisms underlying the synergistic impacts of MQ exogenous aerosols and associated ice-phase clouds on downstream cloud-precipitation processes should be elaborated in detail. Furthermore, it is essential to clarify whether such upstream-to-downstream impacts arise from an individual controlling factor or the compound effects of multiple coupled factors. In addition, it is necessary to explore whether this upstream-downstream transport process is more closely correlated with the occurrence of intense precipitation.

Response 2： Xu et al. (2025) found that, among several factors—including South Asian moisture transport, atmospheric vertical motion, humidity, and aerosols—aerosols played a dominant role in the occurrence of heavy precipitation. The synergistic interaction between the thermodynamic–dynamic forcing over the MQ region and aerosol activation can trigger deep convection over MQ. Specifically, aerosol activation promotes more vigorous cloud development, thereby increasing the likelihood of ice-cloud formation.

Under different large-scale atmospheric circulation backgrounds, these aerosol-activated ice clouds can be efficiently transported downstream along specific pathways, thereby promoting the occurrence of heavy precipitation in downstream regions, as illustrated in Fig. 3. We have also added the accumulated ice-cloud-phase distributions during the preceding 48 h for each day from 9 to 11 July 2018, corresponding to the day of the high-aerosol-loading pollution event and the following two days, together with FLEXPART forward-trajectory simulations for this episode (Fig. S2).A comparison shows that the spatial and temporal evolution of precipitation during 9–11 July 2018 (Figs. S2b–d) is consistent with both the evolving trajectories of ice-phase clouds (Figs. S2e–g) and the FLEXPART-simulated forward trajectories (Fig. S2h). As the event progressed, most of the FLEXPART trajectories were transported at high altitudes. This transport pattern is also consistent with the latent-heat transport trajectories that can represent the movement of ice clouds or ice crystals (Figs. 2a and 2b), as well as with the spatial distributions of ice-cloud- and mixed-phase-cloud anomalies under high- and low-aerosol-loading conditions in July 2018 and July 2019 (Fig. S1). Together, these results reveal a coherent downstream transport pathway through which long-range ice-crystal "seeding" links upstream aerosol activation to downstream cloud and precipitation development. This provides strong evidence that aerosol activation in the upstream region exerts a pronounced ice-seeding effect on downstream cloud-to-precipitation conversion.

The following text has therefore been added to Lines 326-329 of the revised manuscript:

"Comparative analysis shows that the evolution of precipitation during 9–11 July 2018 (Figs. S2b–d) is consistent with both the evolving distributions of ice-phase clouds (Figs. S2e–g) and the FLEXPART-simulated forward trajectories (Fig. S2h). As the episode progressed, most FLEXPART trajectories were transported at upper levels."

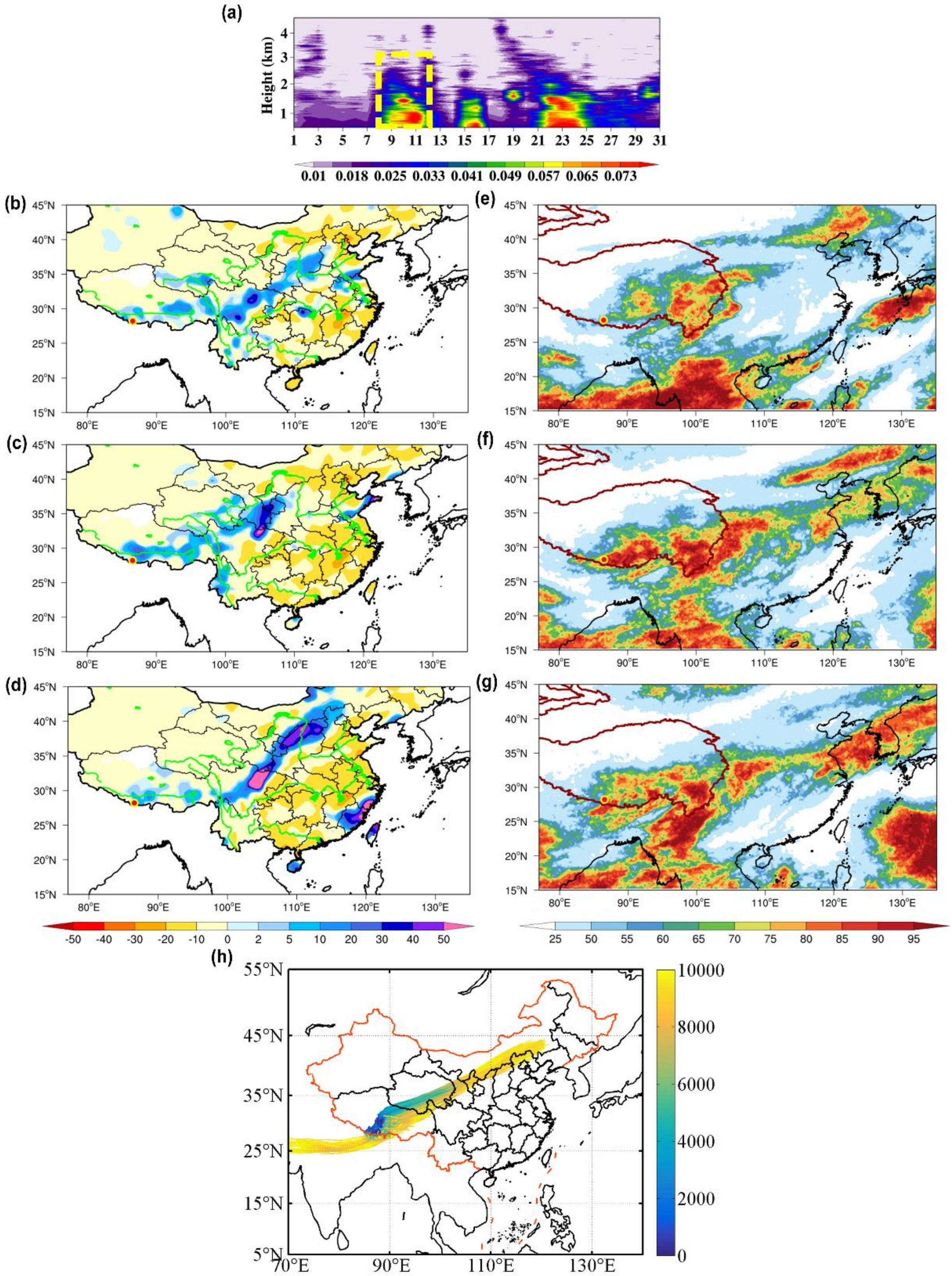

Figure S2. (a) Daily variations in the aerosol extinction coefficient over Mount Qomolangma in 2018. The yellow box indicates the selected high-aerosol-loading episode from 9 to 11 July 2018. (b–d) Evolution of precipitation in the upstream and downstream regions on the day of the high-aerosol-loading event and during the following two days. (e–g) Spatial distributions of ice-phase clouds accumulated over the preceding 48 h for each day of the event. Panels (b, e), (c, f), and (d, g) correspond to the event day, the following day, and the second day after the event, respectively. (h) FLEXPART-simulated forward trajectories for the selected episode (in unit of m with color lines).

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Xu, X. D., Cai, W. Y., Zhao, T. L., Zhang, H., Guo, X. L., Liu, W. Q., Zhang, T. S., Zhao, R. Z., Wu, C., Li, Y. Q., Wang, L., Yan, P., and Yang, C. J.: Understanding clouds and precipitation over the Mount Qomolangma: how does the aerosol activation effect exist?, Sci. Bull., 70, 3649–3658, https://doi.org/10.1016/j.scib.2025.09.031, 2025.

3、This study demonstrates that MQ exhibits high sensitivity to externally transported, high-concentration aerosols, which preferentially enhance ice-phase cloud formation and invigorate deep convective precipitation. The enhanced formation of ice-phase clouds leads to increased latent heat release, intensifying thermodynamic forcing over the TP and altering large-scale circulation patterns. I recommend further elaborating the response characteristics of externally imported aerosols to the MQ heat-pump effect, as well as the corresponding physical feedback mechanisms between externally imported aerosols and the MQ heat-pump effect.

Response 3： Thanks for the reviewer’s suggestions.

Allowing more and smaller cloud droplets to be lifted by the upward air flows due to the superposition of the MQ terrain uplift effect, extending the distance for the collision and coalescence growth of cloud droplets during the ascent along the south slope of the MQ. When a large number of small cloud droplets are lifted to the freezing level forming ice crystals, releasing an additional amount of latent heat energy (Molinié et al. 1995; Williams et al. 2002; Rosenfeld et al. 2006). The additional amount of latent heat energy could intensify the thermal forcing of the MQ (Xu et al., 2019), which can facilitate the convergence of lifting air flows from the south and north slopes. The inevitable result is invigoration of the convective clouds and additional rainfall, despite the slower conversion of cloud droplets to raindrops. That is, clouds gradually thickens with moist and polluted air mass. When cloud tops rise higher and extend further into ice cloud anvils, stronger precipitation can occur (Xu et al., 2025). This is consistent with the theoretical explanation of the "aerosol activation effect" proposed by Rosenfeld et al. (2008). Xu et al. (2025) analysis further reveals the "mutual feedback" mechanism between the activation effect of aerosols on the cloud-precipitation process and the heat source effect of the MQ from the perspective of atmospheric thermodynamical mechanisms, dynamic mechanism triggering deep convection and strengthening precipitation on the MQ. This kind of activation effect of aerosols on the cloud-precipitation process is more prominent at the MQ, “the clean area of the atmospheric environment”.

References

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