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Review

Observational evidence and mechanisms of aerosol effects on precipitation

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A B S T R A C T

Aerosols greatly influence precipitation characteristics, thereby impacting the regional climate and human life. As an indispensable factor for cloud formation and a critical radiation budget regulator, aerosols can affect precipitation intensity, frequency, geographical distribution, area, and time. However, discrepancies exist among current studies due to aerosol properties, precipitation types, the vertical location of aerosols and meteorological conditions. The development of technology has driven advances in current research, but understanding the aerosol effects on precipitation remain complex and challenging. This paper revolves around the following topics from the two perspectives of Aerosol-Radiation Interaction (ARI) and Aerosol-Cloud Interaction (ACI): (1) the influence of different vertical locations of absorbing/scattering aerosols on the atmospheric thermal structure; (2) the fundamental theories of ARI reducing surface wind speed, redistributing water vapour and energy, and then modulating precipitation intensity; (3) different aerosol types (absorbing versus scattering) and aerosol concentrations causing different precipitation diurnal and weekly variations; (4) microphysical processes (cloud water competition, invigoration effect, and evaporation cooling) and observational evidence of different effects of aerosols on precipitation intensity, including enhancing, inhibiting, and transitional effects from enhancement to suppression; and (5) how meteorology, water vapor and dynamics influencing the effect of ACI and ARI on precipitation. In addition, this review lists the existing issues and future research directions for attaining a more comprehensive understanding of aerosol effects on precipitation. Overall, this review advances our understanding of aerosol effects on precipitation and could guide the improvement of weather and climate models to predict complex aerosol-precipitation interactions more accurately.

1. Introduction

Aerosols and their effects on clouds and precipitation exert significant influences on the radiation budget and hydrological cycle [1]. Current studies have improved the understanding of aerosols and precipitation, but knowledge of aerosol effects on precipitation remains limited. Aerosol-Radiation Interactions (ARI) and Aerosol-Cloud Interactions (ACI) are recognized as two key mechanisms of aerosol effects on clouds and precipitation, and their names have evolved from Intergovernmental Panel on Climate Change (IPCC) AR4 to AR5 (summarized in Fig. 1). ARI encompasses the absorption or scattering of solar radiation by aerosols and the subsequent influence of aerosols on cloud evaporation, which can suppress the development of clouds and precipitation [3]. These effects were once considered aerosol direct effects and semidirect effects but were designated radiative forcing (RFari) and the adjustment of ARI in IPCC AR5, and they are both considered to be part of effective radiative forcing (ERFari). The irradiance changes from ACI, encompassing both the cloud albedo effect and lifetime effect, called radiative forcing (RFaci) and adjustment of ACI, are encapsulated as effective radiative forcing (ERFaci) of ACI in IPCC AR5. The cloud albedo effect means that enhanced aerosols increase the cloud droplet number concentration and reduce the cloud droplet effective radius (r_e), thereby augmenting the solar radiation reflected by clouds when cloud water remains constant [4]. However, in specific regions such as the Gulf of Mexico and the South China coast during summer, where abundant water vapour suppresses cloud water competition among droplets, a positive correlation between DER and aerosol optical depth (AOD) has been observed [5]. Increasing cloud condensation nuclei (CCN) concentrations and decreasing r_e can result in prolonged cloud lifetime,

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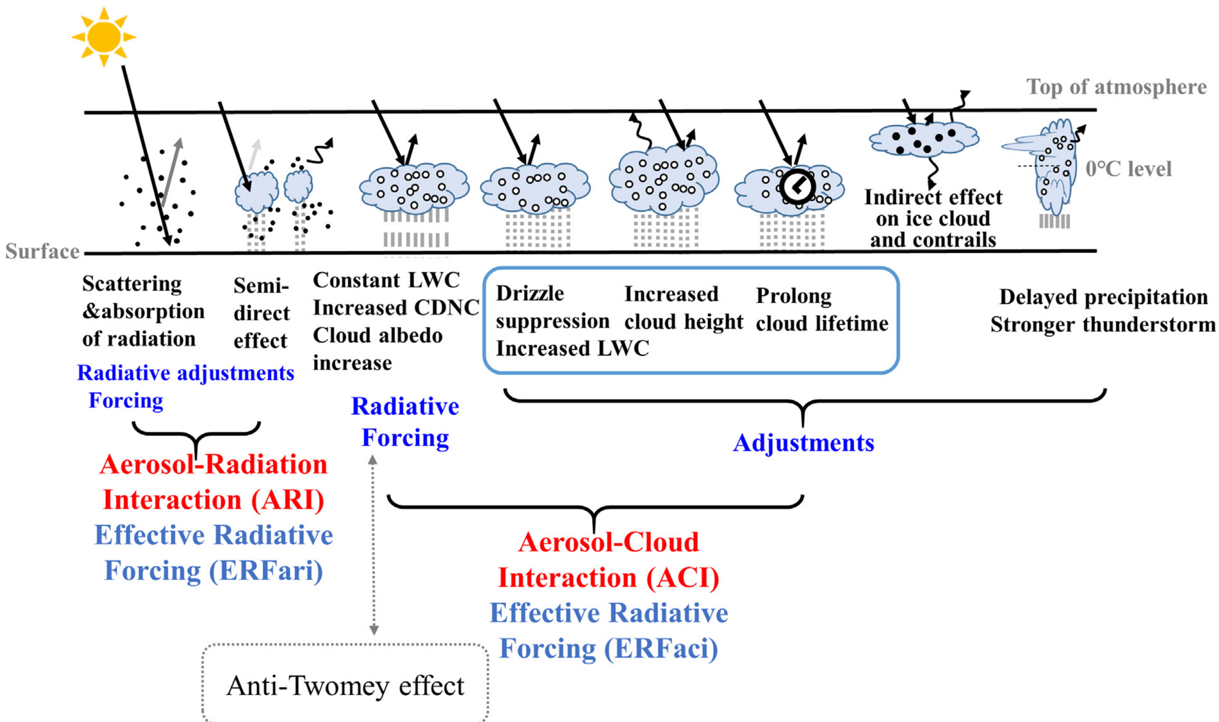

Fig. 1. Illustration of the proposed mechanisms of aerosol effects on clouds and precipitation (adapted from IPCC AR5 [1] and Tao et al. [2]). The black dots represent aerosols, and the black circles represent cloud droplets. The black words represent the names before IPCC AR5, and the colored words are the new name in IPCC AR5.

enhanced cloud cover in relatively clean marine areas, and subsequent reductions in precipitation. This process is referred to as the cloud lifetime effect [6]. The mixed-phase cloud lifetime depends on the balance between CCN and ice nuclei (IN), and clouds will dissipate when the cloud water is removed by freezing and precipitation [7,8]. The glaciation indirect effect caused by IN can produce a positive cloud radiation effect and subsequently affect the radiation balance [9,10]. The effect of aerosols on clouds and precipitation remains an intricate and continually evolving field of exploration [3,6], and some findings have challenged previous theoretical assumptions. For instance, an increase in CCNs and a decrease in r_e may shorten the cloud lifetime, as more small droplets increase the susceptibility to evaporation [10,11]. Furthermore, evaporation cooling enhances the temperature contrast between the cloud edge and core, strengthening relative vorticity of the cloud margin, intensifying convection, and thus promoting precipitation.

Discrepancies in the results have increased the difficulty of understanding the effects of aerosols on precipitation. For instance, a notable study attributed transitions in cloud top height from high to low to increasing aerosol concentrations across the Amazon region [12]. The view is that radiative effects take precedence with low aerosol concentrations, resulting in increased cloud cover, enhanced convection, and minimal attenuation of solar radiation, and microphysical effects come into play with increasing aerosols, competing and interacting with radiative effects. However, the opposite perspective suggests that the aerosol radiative effect is negligible at low aerosol concentrations but gradually intensifies its suppression of convection as the aerosol concentration increases [13]. Altaratz et al. [14] investigated thundercloud responses to aerosols during the Amazon dry season and indicated that ACI initially increases convective intensity and lightning activity, while ARI becomes dominant in suppressing convection as aerosol loading increases. These varied observations underscore the complexity and variability of aerosol effects on clouds and precipitation and promote deeper investigations. Researchers have focused not only on the effects of aerosol concentration changes but also on the different effects of differences in chemical composition. For instance, Sun and Zhao [15] reported that absorbing aerosols tend to advance afternoon precipitation, while scattering aerosols delay precipitation, which results from the different responses of the atmospheric thermal structure to different types of aerosols. Absorbing aerosols heat the atmosphere, thereby promoting convection and precipitation, whereas scattering aerosols exhibit the opposite effect [15,16].

Technological advancements have bolstered instrument detection capabilities, offering us the opportunity to delve even deeper into the effects of aerosols on precipitation. Satellite-based observations, such as those from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Tropical Rainfall Measuring Mission (TRMM), have contributed to more extensive and in-depth studies. Direct evidence that smoke from biomass burning suppresses warm rain and enhances cold rain has been observed through TRMM [17]. The warm rain process is actually terminated in heavily polluted tropical convective clouds, requiring contaminated cloud tops to ascend above the 0 °C level and even to altitudes below −10 °C to produce precipitation, and precipitation predominantly forms before reaching the 0 °C level in clean clouds [17]. In addition, aircraft and radiosonde measurements have provided complementary evidence and revealed that frozen liquid water above the freezing level can generate additional latent heat, thereby promoting deep convective cloud development and delaying precipitation under polluted conditions but potentially leading to more intense thunderstorm precipitation in other regions, which is called the invigoration effect [18,19]. However, the impact of the invigoration effect is not universally significant and can even exhibit inhibitory effects on convection, particularly in the presence of strong wind shear, dry environments, or at the base of cold clouds [20,21]. Recent investigations utilizing satellite data from FengYun (FY), TRMM, Global Precipitation Measurement (GPM), and ground-based radar data have revealed fresh insights into the influence of aerosols on the vertical structure of precipitation [22–24]. The synergistic integration of GPM and FY monitored the processes of cloud vertical evolution and variations in phase, improving the understanding of cloud microphysical processes [22].

Aerosol effects on precipitation are multifaceted and variable, contingent upon aerosol type, aerosol concentration, precipitation type, atmospheric dynamics, moisture, and various other meteorological variables, exhibiting noteworthy regional disparities [20,25–29]. Previous studies have thoroughly introduced the mechanisms and evidence of aerosol-cloud-precipitation interactions, compared modelling and observational results, provided rich information on aerosols and precipitation properties, elaborated the impact of aerosols on the regional climate, and discussed the relationships between large-scale weather and climate events and aerosols [2,8,30]. These reviews focus more on aerosol effects on cloud microphysical properties but less on explaining the effects of aerosol radiation on precipitation. This review complements the studies of aerosol effects on precipitation in recent years and fully explains the effects of ARI on precipitation. This paper also describes the microphysical effects of different aerosols on precipitation and the possible causes of these effects. Alterations in aerosol properties have the potential to induce changes in cloud and precipitation characteristics, encompassing aspects such as cloud/precipitation generation time, precipitation intensity, precipitation amount, and precipitation area. The main objective of this paper is to review these nuanced aspects of aerosol impacts on precipitation or to offer a comprehensive understanding of the underlying mechanisms to compensate for the shortcomings of previous reviews. This review will elaborate in detail on the impact of aerosols on precipitation from two perspectives: ERFari and ERFaci. The paper is organized as follows. Sections 2 and 3 review ERFari and ERFaci, respectively. Section 4 describes the influence of meteorological conditions on ERFari and ERFaci. The summary and discussion are provided in Section 5. Section 6 summarizes the current issues and future challenges and directions.

2. Effective radiative forcing (ERFari)

Aerosols can be categorized into two primary classes, namely, natural and anthropogenic aerosols, based on their sources. Further classification depends on whether they undergo chemical transformations, leading to the distinction between primary and secondary aerosols. Moreover, aerosols can be characterized based on their composition, leading to categories such as dust aerosols, sulfate aerosols, nitrate aerosols, and black carbon aerosols, among others. Researchers often select specific classification schemes tailored to their research objectives. In the study of the effect of aerosols on precipitation, the primary areas of interest revolve around two key aspects: the potential of aerosols to serve as CCN or IN and their capacity to influence the thermodynamic structure of the atmosphere. The latter dimension is commonly divided into two major categories: absorbing aerosols and scattering aerosols. Absorbing aerosols are those with relatively strong absorption efficiency. In contrast to absorbing aerosols, scattering aerosols within the atmosphere primarily stabilize them by diminishing the solar radiation that reaches the Earth's surface. Researchers employ three methods to distinguish between absorbing and scattering aerosols, as shown in Fig. 2. The first method is based on single scattering albedo (SSA). Lee et al. [31] used SSA at a wavelength of 440 nm to differentiate between absorbing and scattering aerosols. An SSA value exceeding 0.95 indicates that the aerosol is the scattering type, while values lower than 0.95 indicate that the aerosol is the absorbing type. Additionally, absorbing aerosols can be further categorized as highly absorbing (SSA < 0.85), moderately absorbing ($0.85 \leq$ SSA < 0.90), or slightly absorbing ($0.90 \leq$ SSA < 0.95). The second method is based on the aerosol index (AI). The AI derived from the Ozone Monitoring Instrument (OMI) aboard the Aura satellite is another valuable tool for distinguishing between absorbing and scattering aerosols. Positive AI values indicate the prevalence of absorbing aerosols in the study area, while negative AI values signify the dominance of scattering aerosols [32,33]. The third method makes use of composition-based assumptions. In scenarios where the regional aerosol composition remains relatively stable, the characteristics of the dominant aerosol components can provide insights into whether aerosols are absorbing or scattering [15,24]. For instance, desert regions, which are primarily characterized by dust aerosols, are dominated by absorbing aerosols [34]. Black carbon is a well-known example of an absorbing aerosol, while nitrate and sulfate aerosols are typically considered scattering aerosols [35]. By employing these methodologies, researchers can effectively distinguish between absorbing and scattering aerosols, enabling a more nuanced exploration of their impacts on atmospheric processes and precipitation.

2.1. The distinct impacts of aerosols on the atmospheric thermal structure

Absorbing aerosols substantially influence the evolution of clouds and precipitation through their capacity to absorb solar radiation. This absorption of solar energy has a series of intricate effects, including the alteration of the vertical thermal structure within the atmosphere and the perturbation of local atmospheric circulation patterns. The effect of absorbing aerosols on precipitation is notably contingent upon the relative positioning of aerosols in relation to clouds, as illustrated in Fig. 3. This critical relationship between aerosol placement and its effects on precipitation has the potential to elucidate and resolve many of the contentious findings that currently pervade the scientific literature.

Absorbing aerosols within clouds could increase cloud temperature, accelerate the evaporation of cloud droplets, and even burn out droplets as a consequence of their absorption of solar radiation. These combined processes collectively render clouds more resistant to precipitation formation or, when precipitation does occur, reduce their magnitude substantially [3,32,36]. Additionally, Costantino and Breon [37] reported intriguing findings that when aerosols and cloud layers are intermingled, there is a significant negative correlation between AOD and r_e. This correlation is likely a result of the intertwined impacts of ACI and ARI. However, their investigation also revealed that when aerosols and cloud layers are segregated, there is no discernible correlation between AOD and cloud droplet r_e, a finding that contrasts with the outcomes of other studies in the field. Absorbing aerosols situated above clouds exert a profound influence on atmospheric conditions [38]. They achieve this by absorbing solar radiation, which in turn elevates the temperature of the air above the cloud layer, reduces atmospheric instability and tends to form an inversion layer. These atmospheric modifications collectively weaken or even hinder the further development of clouds, resulting in a decrease in both precipitation formation and its overall magnitude. Scattering aerosols positioned above cloud layers can similarly suppress the development of clouds and precipitation by diminishing the amount of solar radiation reaching the surface. However, it is worth noting that absorbing aerosols above clouds may increase the cloud fraction. This phenomenon occurs as they absorb solar radiation, subsequently mitigating the entrainment of the cloud top, which contributes to a thickening of the cloud layer [32,39,40]. Notably, Wilcox [32] demonstrated that the direct radiative effect occurring above clouds exerts a stronger influence than the cooling effect resulting from the absorption of aerosols

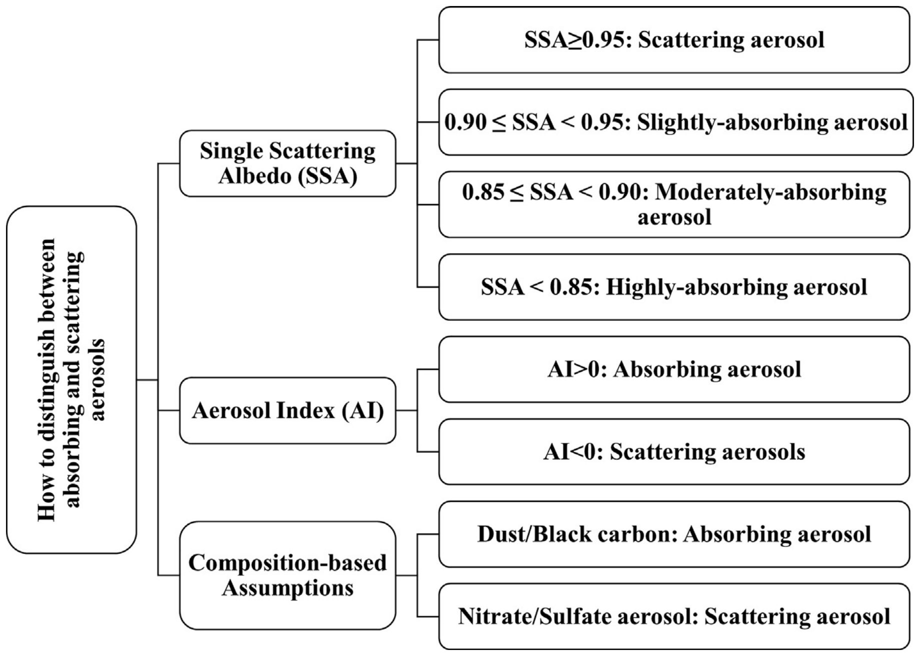

Fig. 2. Three methods to classify absorbing aerosols and scattering aerosols.

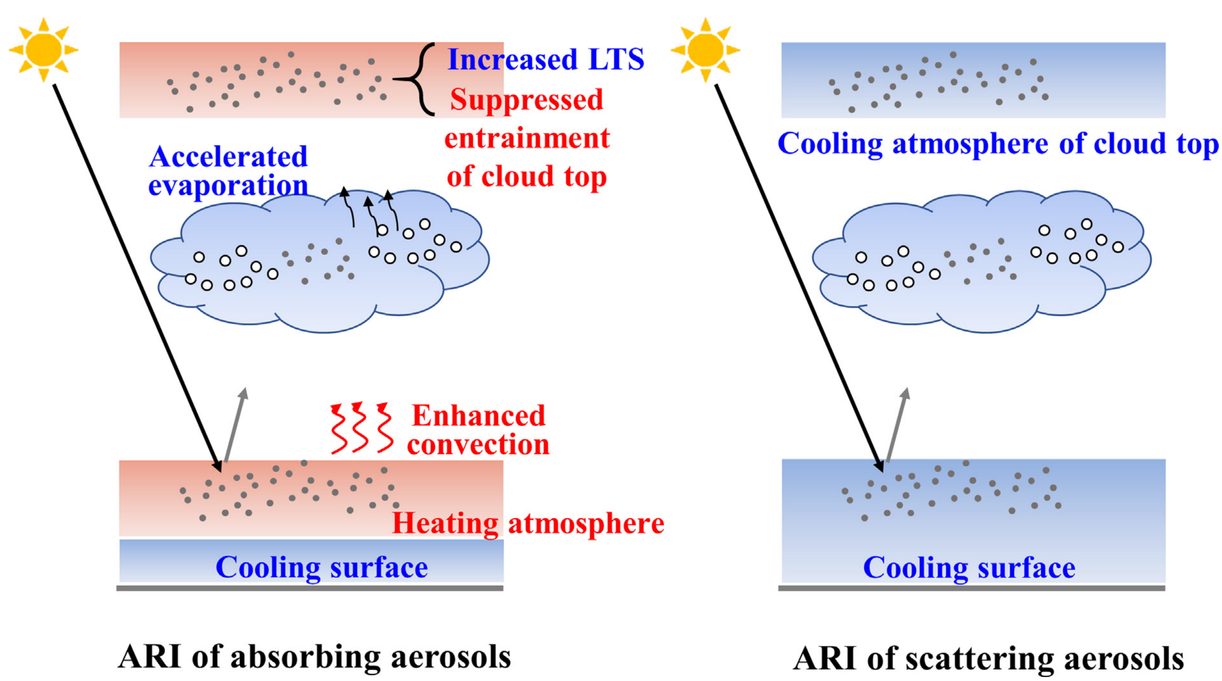

Fig. 3. ARI of absorbing (left) and scattering (right) aerosols due to different aerosol positions. Note that the LTS is low tropospheric stability.

within clouds. Moreover, the suppression of the cloud layer due to the cooling effect can compensate for more than 60% of the thickening of the cloud layer caused by the direct radiative effect over the subtropical South Atlantic Ocean.

Aerosols exhibit diverse behaviours within the atmosphere, and their interactions with clouds and precipitation are influenced by their vertical distribution. Aerosols can either infiltrate cloud formations or hover above them, driven by atmospheric processes such as convection and turbulence. Nonetheless, the majority of aerosols are typically concentrated within the lower atmosphere. Several studies have pinpointed the aerosol layer's location at altitudes ranging from 0.5 to 2 km above the Earth's surface [41,42], with a substantial proportion, often ranging between 60% and 80%, residing at altitudes below 1 km, particularly in urban or industrial regions that have mainly anthropogenic aerosols [35]. Conversely, natural aerosols such as dust and smoke can undergo transport to higher atmospheric levels [27]. Despite attenuating solar radiation reaching the surface, absorbing aerosols can absorb solar energy, thereby increasing atmospheric temperatures. This, in turn, fosters convection and precipitation. Furthermore, absorbing aerosols emit longwave radiation, contributing to atmospheric warming [15]. In contrast, scattering aerosols primarily play a role in cooling the surface, reinforcing atmospheric stability, and suppressing both convection and precipitation. Collectively, the preceding findings underscore that absorbing and scattering aerosols have divergent radiative effects, which consequently have varying impacts on the thermal structure of the atmosphere and then yield discernible consequences for clouds and precipitation.

Continuing our exploration, we delve into the intricate relationship between aerosol radiative effects and precipitation characteristics, drawing upon the literature and fundamental physical insights. Our review encompasses an examination of several key facets, including the impacts on the magnitude, temporal variations, and duration of precipitation. It is crucial to recognize that aerosols can exert a broader influence on the atmosphere by modulating their thermodynamic state, subsequently instigating alterations in large-scale circulation patterns through a variety of feedback mechanisms [43].

2.2. Influence of aerosols on precipitation intensity

ARI plays a pivotal role in modulating precipitation intensity. Wang et al. [44] shared a similar opinion with Jiang et al. [45], namely, that when the AOD surpasses the threshold of 0.3, the direct radiative effect of aerosols inhibits convection and lightning, consequently reducing the probability of afternoon precipitation. Notably, Wang et al. [44] also reported a positive correlation between AOD and lightning flashes, during both the afternoon and nighttime, when AOD levels are below 0.3. These results collectively underscore the nonlinear nature of aerosol radiative effects on clouds and precipitation, signifying that changes in aerosol concentration can trigger a transition from precipitation enhancement to suppression.

ARI can also exert a significant influence on precipitation by impacting wind speed. The direct radiative effect of aerosols can cool the Earth's surface and heat the atmosphere, often resulting in the formation of an inversion layer near the top of the boundary layer. These radiative effects have consequences that include a reduction in vertical turbulence and, consequently, a decrease in the vertical flux of horizontal momentum. This, in turn, leads to diminished water vapour advection and evaporation [46]. Simultaneously, the decrease in wind speed and the attenuation of upper-level wind transport contribute to reduced moisture advection. When coupled with the aerosol second indirect effect, which involves an increase in cloud liquid water content and the subsequent thickening of clouds, these combined influences can lead to a 2%–5% reduction in precipitation amounts, particularly in regions such as California [47].

While previous studies have often attributed decreases in orographic precipitation to reduced wind speed [48], there are also studies highlighting the complex nature of this relationship. For instance, Yang et al. [49] investigated the connection between visibility and precipitation intensity at the Huashan Station in Shaanxi Province, China. They found that aerosols can suppress weak and moderate precipitation while having a relatively insignificant impact on the total precipitation amount and precipitation frequency. This study revealed that aerosol radiative effects reduce the wind speed at the Xi'an Station on the plains but increase it near the mountaintop of Huashan due to compensation mechanisms. This increased wind speed on the mountain reduces the time that air masses spend over the mountain, thereby diminishing mountain precipitation.

In plain regions, aerosol radiative effects reduce surface wind speed by attenuating vertical energy transport, which subsequently suppresses atmospheric instability and convective flows, resulting in a reduction in the vertical flux of horizontal momentum. However, Fan et al. [50] reported different findings in the Sichuan region. They revealed that absorbing aerosols induce a redistribution of both water vapour and energy within the atmosphere. The deposition of heavy pollutants in a basin enhances daytime atmospheric stability, thereby suppressing convection. In contrast, elevated levels of moist air along mountainous terrain increase the intensity of convective activities at night. This intricate interplay significantly amplifies precipitation intensity within the mountainous regions of the Sichuan Basin, consequently causing severe flooding events. These divergent outcomes underscore the necessity of considering local water vapour content and dynamic conditions, which are often intricately linked with aerosol effects on precipitation. Therefore, a comprehensive understanding of aerosol–precipitation interactions should account for the complex interplay between aerosols, atmospheric dynamics, and regional moisture conditions.

2.3. Influence of aerosols on precipitation diurnal and weekly variations

Aerosols exhibit noteworthy diurnal, weekly, and interannual variations, and the characteristics of clouds and precipitation often mirror these temporal patterns [51]. These synchronic trends underscore the considerable potential for aerosols to exert discernible impacts on cloud and precipitation dynamics.

Aerosols have the capacity to significantly alter diurnal variations in precipitation. Guo et al. [25] reported that aerosols can delay heavy precipitation in the afternoon in the Pearl River Delta and explained this phenomenon by combining the effects of ARI and ACI. ARI dominates during the initial stages of convection, while ACI becomes prominent during the subsequent development stage [25]. The interplay between radiative and microphysical effects ultimately leads to the observed delay in precipitation [25,52]. Furthermore, Sun and Zhao [15] have contributed insights into the latitudinal influence on aerosol types and their subsequent effects on diurnal precipitation patterns. They noted that as one moves from the North China Plain to the Yangtze River Delta and further to the Pearl River Delta, the dominant aerosol type shifts from absorbing to scattering. Correspondingly, aerosols introduce a shift in the timing of afternoon precipitation, advancing both the start and peak times of precipitation in the North China Plain, delaying them in the Pearl River Delta, and exhibiting no significant influence in the Yangtze River Delta. This study also underscores the pronounced impact of aerosol concentration on the atmospheric temperature profile. Over the North China Plain, absorbing aerosols are particularly adept at heating the near-surface atmosphere, rendering the lower atmosphere more unstable. Conversely, scattering aerosols over the Pearl River Delta contribute to significant surface cooling, thereby enhancing LTS.

Aerosol concentrations typically exhibit a discernible weekly variation, with higher levels observed on weekdays than on weekends [28,51]. This weekly trend in aerosol concentration is paralleled by corresponding responses in precipitation characteristics. Cerveny and Balling [51] reported a consistent weekly cycle linking air pollution, regional rainfall, and tropical cyclones (TCs) in the coastal northwest Atlantic region. They proposed the hypothesis that aerosols near the surface modify the thermal structure of the boundary layer, resulting in increased turbulence and then enhanced precipitation, and that the aerosols around clouds can absorb solar radiation, thereby promoting clouds and precipitation. Comparable weekly cycles have also been observed in other regions [53,54]. These aerosols, often originating from industrial emissions and vehicle exhaust in urban areas, can impact precipitation patterns. Bell et al. [53] noted that summertime rainfall in the southeastern U.S. is significantly heavier during the middle of the week. In contrast to Cerveny and Balling [51], they postulated that excessive aerosols inhibit raindrop coalescence and warm rain processes, while frozen cloud droplets above the 0 °C layer can release latent heat, thereby intensifying precipitation. Enhanced convection induces regional convergence and uplift, which subsequently results in intensified subsidence in surrounding areas, suppressing further convection. Similarly, Bell et al. [54] reported a similar weekly cycle of lightning activity. Yang et al. [28] revealed opposite weekly cycles in thunderstorm frequency between central China and southeast China, with more frequent thunderstorms occurring on weekends in central China due to the prevalence of absorbing aerosols. They posited that abundant absorbing aerosols tend to suppress convection on weekdays in central China, whereas less absorbing yet more hygroscopic aerosols tend to invigorate thunderstorms on weekdays in southeast China. This observational finding underscores that the relative contributions of ACI and ARI significantly depend on the aerosol type and concentration. In essence, the findings described above illuminate the complex and multifaceted interplay between aerosol characteristics and weekly precipitation cycles, highlighting the need to consider aerosol type and concentration as key factors in understanding their effects on regional precipitation patterns.

3. Effective radiative forcing (ERFaci)

Aerosols can alter precipitation by serving as CCN/IN, a key element in the process of ACI [30]. The CCN is intricately linked to the particle composition, particle size, volume fraction of organic material, aerosol hygroscopicity, growth stage (whether the particles are fresh or aged), and aerosol oxidation level [16,55]. The IN concentration is affected by ice supersaturation, temperature (usually below 0 °C), particle size, and particle composition, such as mineral dust, soot, organic matter, and biological aerosols [8,30]. Only a small fraction of aerosols can serve as efficient IN, with approximately 1 IN for every 10^5 CCN aerosols [8]. Released particles require time to ascend into the clouds, and the adjustment of cloud properties, such as r_e, the liquid water path (LWP), and macroscopic characteristics, in response to aerosols also requires time of up to several hours or even more to manifest a significant change [56]. In the quantitative assessment of aerosol effects on precipitation, it is imperative to consider the time dependence of these processes. Regrettably, quantifying the impact of ACI on precipitation poses formidable challenges. These challenges arise not only from the complexities of time-dependent data alignment but also from the profound influence of shifts in atmospheric dynamics and thermodynamics on cloud and precipitation responses to aerosols [57,58]. Consequently, a cautious and comprehensive consideration of these influential factors is paramount when endeavouring to unravel the intricate relationship between aerosols and precipitation.

3.1. Aerosols can either enhance or inhibit precipitation

The influence of ACI on precipitation intensity exhibits a diverse range of outcomes, encompassing enhancement, suppression, and nonmonotonic responses. This variability can be attributed to the complex interplay of processes within clouds. As the CCN number concentration increases, more cloud droplets tend to form due to the activation process, while the growth rate of droplets could decrease due to the consumption of water vapour. The ease with which cloud droplets transform into raindrops hinges on the competition among several mechanisms, including cloud water consumption by condensation, convective invigoration (which enhances supersaturation), collision-coalescence, and evaporation. The dominance of these mechanisms is contingent upon factors such as water vapour content, aerosol concentration, and aerosol type. When water vapour is abundant, an increase in aerosols can facilitate the growth of cloud droplets by enhancing the collision-coalescence efficiency, thereby promoting precipitation. Conversely, when water availability is limited, an increase in aerosols can reduce cloud r_e, thus suppressing precipitation [6,59]. Absorbing aerosols can further decrease the likelihood of precipitation occurrence by heating the cloud layer and promoting evaporation. It is important to emphasize that these mechanisms can coexist and compete with each other, leading to different outcomes. An increase in aerosols can theoretically lead to more INs, promote heterogeneity, and increase the effective radius of ice crystals (r_{ei}) [60], while the effects of aerosols on r_{ei} are complicated in practical situations [60,61]. Graupel particles usually grow much faster than supercooled raindrops due to the more efficient collision-coalescence process, so increased IN can accelerate precipitation-forming processes efficiently [62]. The following provides a comprehensive summary of the effects of ACI on precipitation intensity.

Numerous studies have consistently observed that aerosols exert an influence on precipitation by reducing cloud r_e through cloud water competition, which subsequently hampers the collision and coalescence process. By comparing the trend of precipitation changes in polluted or heavily polluted areas with that less affected by pollution, it has been found that precipitation significantly decreases in polluted areas [16,63]. A study by Stjern et al. [64] conducted over the formerly heavily industrialized region known as the Black Triangle revealed that aerosols had no discernible impact on the total precipitation frequency but did inhibit weak precipitation. Guo et al. [13] associated the decreasing trend of local-scale precipitation frequency with increasing aerosols over eastern China in summer by separating the influence of local thermodynamic conditions and humidity. These studies, often conducted in heavily polluted regions, hold practical significance for understanding the complex relationship between aerosols and precipitation, such as in East Asia.

The enhancing effect of aerosols on precipitation has been consistently documented in numerous studies [57]. Koren et al. [65] performed a systematic analysis based on observations over the North Atlantic Ocean and revealed that aerosols have the capacity to invigorate convective clouds through an effective increase in the cloud fraction and cloud top height. Zhu et al. [66] reported that the height of rain initiation increases by ~5.5 km with a unit increase in AOD over Southeast Asia and adjacent seas during summer, which implies that aerosol can strengthen convective and the development of cold clouds and precipitation. Based on satellite data, Zhang et al. [67] found that dust provides abundant effective INs to glaciate mixed-phase clouds over East Asia and produce additional latent heat to bolster the further development of clouds. Their study revealed that mineral dust can generate glaciated cloud fractions approximately 5%, 10%, and 20% greater than those of polluted dust, smoke, and background aerosols, respectively, at any given cloud top temperature in subfreezing clouds. Previous studies have shown that increased INs can enhance ice phase and mixed-phase precipitation. For example, many studies have shown that long-range transport of dust from Asia can increase snow precipitation in California [68,69]. Fan et al. [70] found that ultrafine aerosols can even be activated as CCN in deep convective clouds in the Amazon region. Compared with the proposed precipitation invigoration effect by Rosenfeld et al. [19], this activation of ultrafine aerosols is more efficient in enhancing condensation, ultimately amplifying convection and precipitation.

The suppression of warm rain and enhancement of cold rain by aerosols under heavy pollution conditions have been widely observed in numerous studies. Aerosol-induced suppression of warm rain results in a greater number of cloud droplets ascending, where they freeze and release latent heat through the freezing process before precipitating. Delayed precipitation leads to more significant and persistent updrafts and invigorates convection before precipitation-induced downdrafts take over [18,65,71]. Several studies have shown that aerosols tend to suppress light precipitation and enhance heavy precipitation but have nonsignificant effects on interannual and seasonal total precipitation [72,73]. Fan et al. [72] emphasized the substantial impact of aerosols on the redistribution of the rain rate, emphasizing the importance of considering precipitation intensity rather than solely focusing on the total precipitation amount in the study of aerosol effects on precipitation. The influence of aerosols on the distribution of precipitation rates is likely linked to daily accumulation increases [74]. The mechanism of heavy precipitation increase with aerosols is generally elucidated as follows: Heavy precipitation events typically coincide with ample water vapour supply, leading to increased liquid water content, enhanced cloud droplet growth, higher collision efficiency, and the presence of invigoration effects that intensify with increased aerosol concentrations. However, a model study conducted by Shao et al. [75] indicated that anthropogenic aerosols enhance upwards motion and increase the cloud water path and effective radius through ARI, which is considered a primary reason for the intensification of heavy precipitation. Additionally, ARI and ACI often work in tandem to reduce moderate and light precipitation [75].

Numerous observational studies have provided evidence that ACI can significantly modify the track, intensity, size, and lifespan of tropical cyclones (TCs). For instance, Yang et al. [76], drawing on 35 years of observational data on AOD and TCs, found a positive relationship between the relative percentage of TC rainstorm days, the intensity of TC daily precipitation, and AOD, especially during the initial TC period and for heavy TC rainfall. Zhao et al. [77] ascertained that anthropogenic aerosols have the capacity to increase both the TC rainfall amount and the TC rainfall area in the western North Pacific. Quantitatively, they found that TC rainfall increases by 9–20 km for a 0.1 increase in AOD. Most studies attribute the impact of aerosols on TCs to both microphysical and radiative effects. Through microphysical effects, aerosols, by serving as CCN, cause more droplets to grow with the help of abundant water vapour within TCs, releasing latent heat and promoting convection and precipitation. Moreover, aerosol radiative effects typically influence the generation and development environment of TCs. For example, Evan et al. [78] leveraged observational, reanalysis, and model simulation data to investigate anomalous circulation patterns and found reduced basin-wide vertical wind shear by radiative forcing of anthropogenic aerosols, which is conducive to the intensification of TCs over the Arabian Sea. Additionally, Sun and Zhao [26] reported that dust aerosols can suppress sea surface temperature, reduce low-level specific humidity, promote wind shear, and induce positive relative vorticity, all of which further influence the development of TCs in the TC genesis region.

3.2. Boomerang variation effect of aerosols on precipitation

Numerous studies have documented a boomerang variation in the relationship between aerosols and precipitation, characterized by initial enhancement followed by suppression, which has been observed over various regions, including eastern China [13,79], tropical oceans [80], and the North China Plain [24]. However, the explanations for this phenomenon vary considerably among studies. Guo et al. [13] reported that increased aerosols facilitate the cloud-to-precipitation conversion process under clean conditions, while cloud-water competition suppresses the growth of cloud droplets under polluted conditions, leading to a subsequent decrease in precipitation. Liu et al. [80] attributed the nonlinear effect of aerosols on clouds and precipitation in tropical oceans to the competition between the invigoration effect in the cloud core and the suppression process at the cloud edges, emphasizing the pivotal role of microphysical processes in driving this nonlinear response. In addition to the nonlinear effect from invigoration to suppression, Sun et al. [24] further found that the competition between evaporation cooling and released latent heat can cause the precipitation top height to increase first and then decrease. As shown in Fig. 4, the growth of cloud droplets does not excessively consume cloud water, and the released latent heat increases, while evaporative cooling does not change significantly under clean conditions, which is contrary to the situation under polluted conditions. This makes the precipitation top height the highest under moderate pollution conditions [24]. The precipitation area also shows a boomerang variation in aerosols that first increases and then decreases with increasing AOD under polluted conditions [81].

Several studies have suggested that whether aerosols enhance or inhibit precipitation depends on factors such as water vapour, cloud/precipitation development stage, aerosol type, aerosol concentration, and precipitation type. For instance, Sun et al. [79] reported that aerosols tend to promote precipitation development when the AOD is below 0.5, whereas they exhibit a suppression effect when the AOD surpasses 0.5 in eastern China. Note that the threshold value is related to the aerosol composition and the adequacy of the water vapour supply. Guo et al. [82] argued that the promotion or suppression effect of aerosols depends on the developmental stage of clouds and precipitation. In the initial and dissipation stages of clouds and precipitation, aerosols tend to have a suppressing effect, while during the mature stage, they generally intensify the development of clouds and precipitation. Specifically, when the maximum precipitation rate is above (below) 30 mm/h, aerosols promote (inhibit) precipitation development. Jiang et al. [26] reported that aerosol type is another crucial determinant of the impact of aerosols on convective clouds. Specifically, smoke aerosols tend to have a suppressive effect, while polluted continental aerosols tend to invigorate convective clouds. Furthermore, Yang and Li [83] found that aerosols can invigorate daily precipitation amounts during thunderstorm days in plain regions compared to high-altitude regions. This difference is attributed to the accumulation of aerosols in plain regions, highlighting the importance of geographical location in aerosol-precipitation interactions. Dust aerosols can enhance ice and mixed phase precipitation and suppress warm rain due to the increase in heterogeneous ice nucleation [84,85]. The IN effects generally work for ice/mixed phase precipitation. The microphysical effects induced by dust are more evident for stratiform precipitation than convective precipitation in the tropics [84,86], while the opposite result is found in China [85]. This may be attributed to the prevalence of warm convective precipitation and cold stratiform precipitation over the ocean, whereas the opposite is observed over land. Many studies have shown that convective precipitation is more sensitive to aerosols than stratiform precipitation [15,79], and the responses of convective and stratiform precipitation to aerosols are different [23].

3.3. Effect of aerosols on the vertical structure of precipitation

In recent years, research on precipitation has expanded beyond the near-surface or within-cloud focus and shifted towards studying the vertical structure of precipitation. Rosenfeld et al. [19] proposed that deeper clouds at higher altitudes can generate stronger surface precipitation, and this viewpoint has been affirmed by Zhu et al. [85]. However, Sun et al. [24] found that absorbing aerosols near the surface can enhance evaporation, resulting in a change in the net impact of aerosols on precipitation during the falling process; therefore, the near-surface precipitation rate shows no significant response to aerosols and precipitation top height, which is inconsistent with the conventional notion that higher and thicker clouds are associated with greater precipitation rates. Some studies have also shown that aerosols have different impacts on

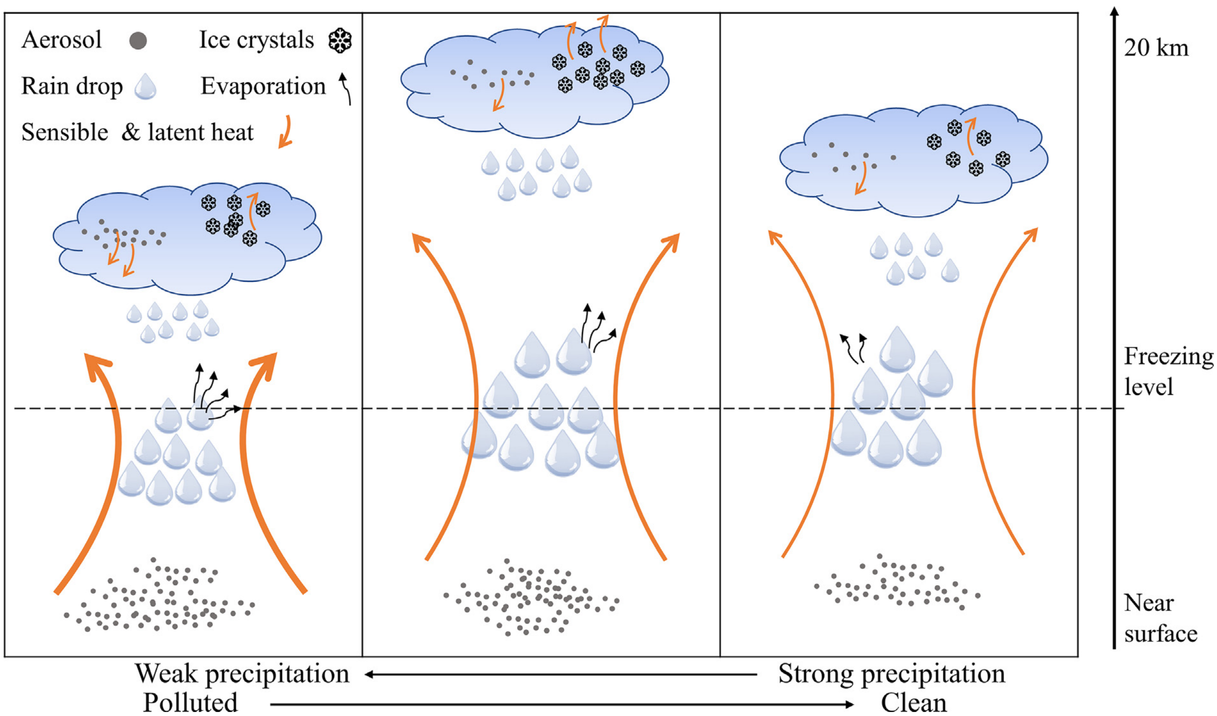

Fig. 4. Theoretical framework of the vertical dependency of aerosol impacts on local-scale convective precipitation.

precipitation at different altitudes. For example, Sun et al. [79] reported that aerosols enhance the convective precipitation rate from the surface to 5 km but suppress it above 5 km over middle and east China.

Dust can be transported to higher altitudes, and its vertical distribution often affects the vertical characteristics of precipitation. Dust aerosols enhance the precipitation rate above the freezing level due to heterogeneous ice nucleation [86], and dust enhances the breakup process of raindrops when convective rain occurs at and below the dust layer due to heated air [84]. Zhu et al. [85] reported that dust aerosols increase the growth rate of raindrops at temperatures between −5 and 2 °C due to the presence of more ice-phase hydrometeors in this temperature range.

4. The influence of meteorological conditions on ACI and ARI

The impacts of meteorological variables and aerosols on precipitation are coupled, and how to separate the effects of meteorological variables and aerosols on precipitation has always been a matter of concern. Several studies have shown that the effect of aerosols on precipitation intensity can be affected by meteorological variables [24,57,58]. In addition, aerosols can induce significant variations in meteorology, for example, increased relative humidity and destabilization due to the aerosol invigoration effect [87]. These changes in meteorology can further influence cloud and precipitation processes, creating a complex interplay between aerosols and meteorological variables.

Xiao et al. [88] conducted a study on the influence of aerosols on precipitation rates in North China during autumn and winter from 2014 to 2021. They found a significant positive relationship between the two variables, and this positive correlation was independent of key meteorological factors such as precipitable water vapour, LTS, and wind shear. Interestingly, they also noted that under weak dynamic conditions, the positive correlation between aerosols and the precipitation rate became more pronounced. This suggests that aerosols play a substantial role in influencing precipitation in this region, and their impact is not easily reversed or overridden by prevailing meteorological conditions. In contrast, other studies have shown that meteorological conditions can indeed influence the aerosol effect. For instance, Zhong et al. [89] reported that when synoptic forcing is weak, ARI can dominate local convergence, potentially suppressing the development of clouds and precipitation. Conversely, when the weather forcing is strong, the aerosol effect is attenuated. These studies underscore the importance of considering atmospheric conditions when evaluating the net effect of aerosols on precipitation.

Many studies suggest that meteorological factors such as dynamics and water vapour can modify the effects of aerosols on clouds and precipitation. Dynamics are often characterized by parameters such as updraft strength, wind shear, atmospheric stability, and convective available potential energy (CAPE) [2,20,57]. These factors can profoundly influence the development of clouds and precipitation and their interactions with aerosols. Water vapour-related variables include relative humidity, specific humidity, precipitable water vapour, and LWP [24,71,87]. Meteorology can affect the generation and development of precipitation and regulate the distribution of aerosols, possibly leading to a bias (overestimation or underestimation) in the effect of aerosols on precipitation and even a significant change in the correlation between aerosols and precipitation.

LTS conditions are a crucial indicator of the atmospheric environment, particularly the presence and intensity of the inversion layer that caps the planetary boundary layer [90]. A low LTS signifies an unstable atmosphere, which is highly conducive to the development of convection [25,91]. Sun and Zhao [27] reported that aerosol effects on precipitation are significant under low relative humidity or weak LTS. Wind shear is another meteorological factor of considerable significance when assessing the effects of aerosols on precipitation. Weak wind shear favours the enhancement of aerosol effects, while strong wind shear inhibits them. The mechanism underlying this phenomenon is rooted in the impact of wind shear on atmospheric convection. Aerosols typically weaken near-surface wind speeds while having a minimal effect on upper-level wind speeds. As a result, wind shear increases, leading to the suppression of intense convection. This also hinders the transport and diffusion of aerosols from the surface to higher levels, further exacerbating aerosol effects on precipitation and amplifying wind shear, which is unfavourable for the occurrence of intense convection and other chain reactions [20,27]. The CAPE represents the potential energy in the atmosphere, which is determined by the total excess buoyancy. Large positive values of CAPE imply that an air parcel would be significantly warmer than its surrounding environment. In fact, CAPE is the primary driving force for the total precipitation produced by storms. Notably, Storer et al. [92] found that aerosol effects on clouds and precipitation tend to be more pronounced with weaker CAPE. They compared the responses of cloud and precipitation characteristics to aerosols and CAPE and found that the cloud water path is more sensitive to aerosol concentration than CAPE, while the responses of the ice water path to aerosols and CAPE are similar. In addition, they found that the mean raindrop diameter has little response to CAPE but a substantial response to aerosol concentration.

Both observational and simulation studies suggest that the effects of aerosol are sensitive to water vapour conditions [27,93]. Abundant water vapour is conducive to enhanced convection and precipitation by aerosols; in contrast, aerosols suppress precipitation with insufficient water vapour supply, which may result in humid areas becoming wetter and arid areas becoming drier [65,71,94]. Using global satellite data, Niu and Li [95] reported that this phenomenon is not limited to isolated ground locations but is observed over various regions and is even more pronounced in tropical regions. Notably, the phenomenon called the "southern-flood-northern-drought" pattern in summer over China is partially attributed to the influence of black carbon (absorbing aerosol) on large-scale circulation and the hydrologic cycle via ARI [96]. The aerosols invigorate and suppress lightning under low and high aerosol loading conditions over dry regions, respectively, while the aerosol-invigoration effects are sustained under both low and high aerosol loading conditions under moist regions [97]. Furthermore, in warm and humid summers, strong surface sensible heat and latent heat fluxes favour the generation of intense convection, and aerosols are more likely to enhance convection and promote precipitation [19,71]. In contrast, during cold and dry winters, aerosols tend to inhibit the development of convection and precipitation.

5. Summary and discussion

The IPCC's 6th annual report [1] highlights a significant knowledge gap and low confidence in our understanding of precipitation compared to temperature within the context of global warming. Emerging evidence suggests an increase in the frequency of extreme precipitation events, leading to increased flood exposure and threatening to human life and property [98]. It is imperative to recognize that the impact of human activities on cloud physical processes is the most substantial source of uncertainty in climate change projections. Moreover, the emissions of greenhouse gases and aerosols resulting from human activities play pivotal roles in shaping these uncertainties. Therefore, the study of aerosol effects on precipitation represents a crucial yet formidable challenge within the realm of climate science.

This review provides a detailed review of the observational findings and underlying mechanisms concerning the impact of aerosols on precipitation over the past few decades with the following key points.

First, the impacts of aerosols on clouds and precipitation vary depending on their position relative to clouds. Absorbing aerosols below clouds can cool the surface and heat the atmosphere, which can promote convection and precipitation overhead. Absorbing aerosols above clouds can cool cloud top temperatures and tend to reduce evaporation and entrainment to increase cloud thickness, but aerosols can also enhance LTS and subsequently inhibit the development of clouds and convection. Absorbing aerosols inside clouds can promote cloud evaporation and shorten the cloud lifetime. Scattering aerosols can reflect solar radiation, cool the surface, and suppress convection and precipitation.

Second, ARI can modify the atmospheric thermal structure and subsequently affect the precipitation intensity and precipitation diurnal and weekly variations. The aerosol radiative effect on precipitation is sensitive to aerosol concentration and type. Heavy pollution can reduce the amount of solar radiation reaching the surface and then suppress convection and precipitation via direct radiative effects. Absorbing aerosols can advance the start time of precipitation in the afternoon, while scattering aerosols generally delay it. Additionally, ARI can decrease the surface wind speed, increase the upper-level wind speed, and then spatially redistribute water vapour and energy, thereby affecting precipitation.

Third, ACI can both enhance and suppress precipitation and even show a transition variation from enhancement to suppression with increasing aerosol concentration due to competition among underlying mechanisms such as cloud water competition, invigoration, and evaporation. The impact of ACI on precipitation depends on factors such as water vapour, cloud/precipitation development stage, aerosol type, and aerosol concentration. Aerosols generally suppress warm rain and enhance cold rain.

Fourth, aerosols usually suppress light precipitation and enhance heavy precipitation but have nonsignificant effects on interannual and seasonal total precipitation. The CCN number concentration, water vapour content, aerosol type and dynamics can affect the collision and coalescence efficiency, which is an important pathway for cloud droplet conversion to raindrops and subsequently affects the formation and development of precipitation. In addition, ACI and ARI can increase the TC rainfall amount, decrease the TC rainfall maximum intensity, and increase the TC rainfall area. Moreover, ARI can influence the meteorological environment for the generation and development of TCs.

Finally, the sensitivity of aerosol effects on meteorology is discussed in detail, primarily from two perspectives: dynamics and water vapour. Aerosol effects on clouds and precipitation are more significant under low humidity and weak dynamic conditions. Wind shear inhibits the aerosol effect. Abundant water vapour, a large positive CAPE, and a low LTS are all conducive to enhanced convection and precipitation.

Although we have introduced ACI and ARI separately to highlight their impacts and differences, it is essential to recognize that, in practical applications, we should consider both effects comprehensively. In this study, we described in detail the impact of aerosols on precipitation, but we did not put much effort into classifying the types of precipitation. Notably, the types of precipitation are crucial for fully understanding the impacts of aerosols on precipitation. For example, Sun and Zhao [15] reported that convective precipitation is more sensitive to aerosols than stratiform precipitation. Day et al. [74] also found a positive correlation between the frequency of frontal precipitation and aerosols, while no significant relationship was found for large-scale precipitation. This discrepancy may be attributed to the fact that convective precipitation is often associated with strong vertical air motion, which provides a more favourable environment for aerosols to interact with clouds.

6. Challenges and suggestions for future studies

Although extensive studies have been conducted on clouds and precipitation, we still have limited knowledge about the mechanisms of cloud and precipitation formation and development, as well as a limited understanding of their internal structure. More refined data are a prerequisite for addressing this knowledge gap.

For example, Fan et al. [70] reported that ultrafine particles with diameters even smaller than 50 nm can serve as CCN in the Amazon region under certain (highly unstable) conditions, which is supported by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement program 1290-MHz Ultra High Frequency (UHF) Radar Wind Profilers (RWP) observations during GoAmazon 2014/5. Additionally, the FY and Himawari satellites provide data support for further understanding the structure of clouds and precipitation [22,99,100]. Furthermore, the continuity of data in time and space is also worth considering, as different conclusions from various studies on the same issue often result from disparities in data sources, study periods, and study regions, suggesting pronounced spatial and temporal variations in precipitation and aerosol properties. Precipitation and aerosol properties may exhibit pronounced variability at short timescales, such as during the initial, mature, and dissipation stages of clouds and precipitation [99,100], which is a significant challenge for the study of aerosol-precipitation interactions [99,100]. Finally, researchers should closely monitor changes in aerosol composition and concentration. In recent years, China has witnessed significant improvements in air quality, accompanied by shifts in aerosol composition, which will have a significant influence on ARI, as mentioned by Li et al. [30]. Therefore, staying attuned to evolving aerosol characteristics is paramount for advancing our understanding of aerosol-precipitation interactions, especially the vertical aerosol distribution.

Distinct observational datasets possess unique merits, and the synergistic integration of these data promises to offer unprecedented advantages for future research endeavours. However, it is important to note that these studies share a common limitation, wherein ground-based $PM_{2.5}/PM_{10}$ mass concentration or AOD is utilized as a proxy for CCN or cloud droplet number concentration. This introduces significant uncertainties and poses challenges for conducting precise quantitative investigations. Pan et al. [58] provided an alternative perspective in which fine particulate matter more accurately represents CCN than coarse particles. This fresh perspective on data selection opens new avenues for research and underscores the importance of selecting appropriate metrics for precise quantitative analysis in future studies. The role of precipitation in aerosols, such as wet scavenging processes, and the process by which aerosols influence precipitation are closely intertwined. However, in current research, we seldom consider both simultaneously. We can employ the models to achieve this requirement. These observations provide new evidence regarding the aerosol effect on precipitation, and these new findings should be promptly incorporated into cloud-resolving models to help us understand basic physical processes. Most studies have examined the impact of aerosols on precipitation from a small-scale perspective, yet in reality, aerosols and precipitation can influence the regional climate and even the global water cycle. Understanding how aerosols affect climate feedback to local aerosol and precipitation characteristics is also an important issue.

Another key issue in understanding the aerosol effect on precipitation is effectively and reliably distinguishing the response influenced by aerosols from other meteorological parameters [87]. In observational studies, the commonly employed research method is the variable control method, which entails observing how clouds and precipitation respond to aerosols under varying meteorological conditions. Recently, Zang et al. [87] used a machine learning method to separate and quantify the aerosol invigoration effect, and covarying meteorological conditions further induced invigoration. The adoption of more effective and robust study methodologies will be imperative in future research endeavours. Moreover, the feedback of precipitation on aerosols, including the wet scavenging effect of precipitation on aerosols, aerosol hygroscopic growth with enhanced humidity, and increased aerosols from cloud evaporation, should also be considered in the future. A comprehensive understanding of these bidirectional interactions will be instrumental in advancing our comprehension of aerosol–precipitation relationships in future studies.

Conflict of interest

The authors declare that they have no no conflict of interest.

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Author Contribution

Professor Chuanfeng Zhao is the first and corresponding author of this paper, who contributed to the original draft, writing-editing and review. Yue Sun contributed to the original draft and writing-editing. Jie Yang and Jiefeng Li provided related materials and writing-editing. Yue Zhou, Yikun Yang, Hao Fan, and Xin Zhao contributed to writing-editing and provided some valuable suggestions for this paper before submission.

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