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Review Article

Aerosol Effects on Instability, Circulations, Clouds, and Precipitation

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It is well known that increasing aerosol and associated changes in aerosol-cloud interactions and precipitation since industrialization have been playing an important role in climate change, but this role has not been well understood. This prevents us from predicting future climate with a good confidence. This review paper presents recent studies on the changes in the aerosol-cloud interactions and precipitation particularly in deep convective clouds. In addition, this review paper discusses how to improve our understanding of these changes by considering feedbacks among aerosol, cloud dynamics, cloud and its embedded circulations, and microphysics. Environmental instability basically determines the dynamic intensity of clouds and thus acts as one of the most important controls on these feedbacks. As a first step to the improvement of the understanding, this paper specifically elaborates on how to link the instability to the feedbacks.

1. Why Is Aerosol Important in Our Understanding of Climate Change?

In the last decades, observational studies suggested that climate has been changing since industrialization. Increases in green-house gases have been believed to play a major role in climate change. Anthropogenic activities that cause the increases in green-house gases generally involve the enhancement of aerosol concentration. For example, emissions of exhaust gas by cars contain not only carbon dioxide (the well-known representative green-house gas) but also aerosol particles. Numerous studies over the last decades have demonstrated that these increases in aerosol concentration have a significant impact on climate change (e.g., [1–3]). Hence, to better predict and cope with climate change, it is imperative to identify the role played by increasing aerosol in climate.

Clouds not only intercept solar radiation to control the net energy budget and temperature in the Earth but also produce precipitation which is essential to maintain life on the Earth. In particular, rain which forms in convective clouds with strong updrafts produces most of the precipitation on a global average basis [4]. Hence, convective clouds are important for determining the relationship between aerosol and precipitation and thus the effect of the relationship on precipitation and global hydrologic circulation that are important aspects of climate. Recent studies have shown that increasing aerosol concentration since industrialization has significant impacts on cloud particles and precipitation in convective clouds and thus on global hydrologic circulations [5–12]. In this review paper, recent studies on the effects of aerosol on convective clouds and their precipitation are introduced and discussed. This intends to shed light on new findings of aerosol-cloud interactions in convective clouds and their conceptual basis for scientists involved in the field of the interactions. In Section 2, important factors which are recently identified to control the effects of aerosol on convective clouds are explored and discussed. In Section 3, future work for a better representation of the effect of aerosol on convective clouds in models is proposed and discussed.

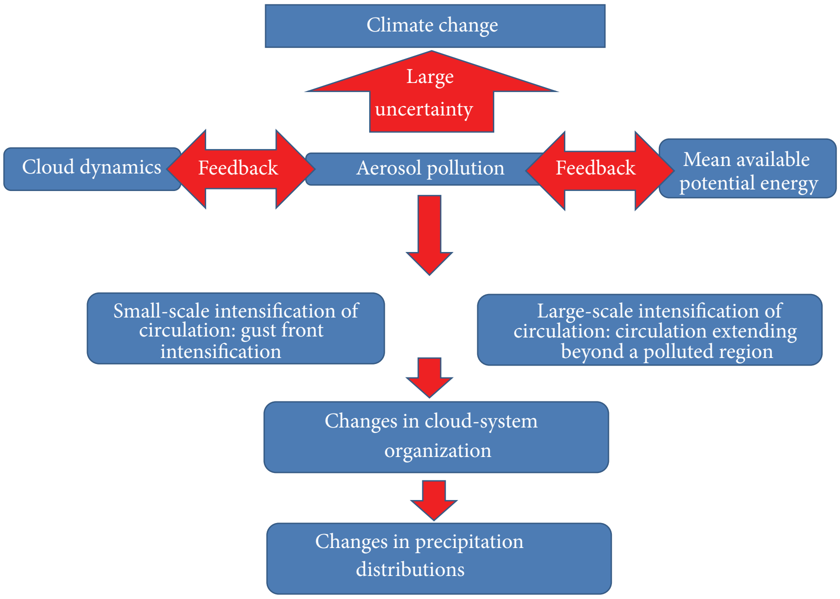

Figure 1: Schematic diagram illustrating the flow of this paper.

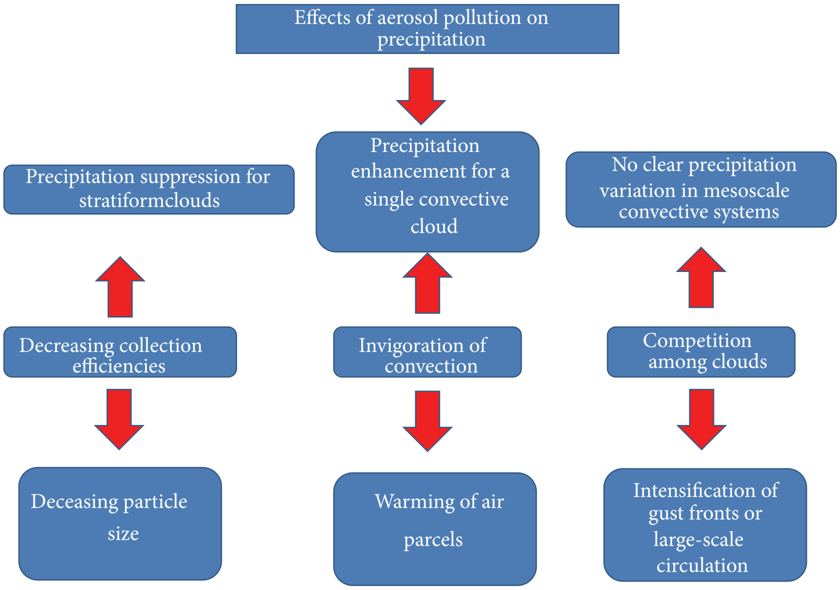

Figure 2: Schematic diagram illustrating differences in precipitation responses to aerosol perturbation among cloud types.

Overall flow of this paper is depicted diagrammatically in Figure 1. Figure 2 diagrammatically summarizes differences in precipitation response to increases in aerosol concentration and associated mechanisms among different types of clouds based on discussions in the following sections.

2. What Are the Important Factors?

2.1. Cloud Dynamics. Recent studies over the last decade have shown that, for the better and comprehensive understanding of the effects of aerosol on convective clouds, we need to consider cloud dynamics as well as cloud microphysics [5, 6, 8, 13–18]. It is well accepted that increasing aerosol or aerosol perturbation induces the microphysical alteration of clouds, which is the alteration of cloud-particle sizes. This inevitably involves changes in latent-heat absorption and release [19], leading to those in cloud dynamics. The changing cloud dynamics affects the growth of cloud particles or cloud microphysical processes and this establishes feedbacks among aerosol, microphysics, and dynamics. Recent studies on these feedbacks have shown that these feedbacks (involving cloud dynamics) can lead to the effect of aerosol on clouds, which is counterintuitive to the traditional understating of aerosol-cloud interactions as proposed by Twomey [20] and Albrecht [21]. For example, some of these

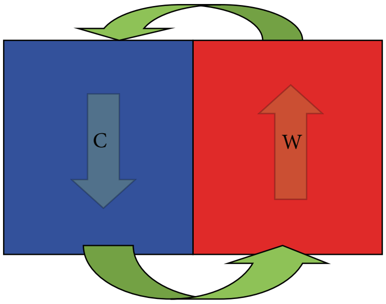

Figure 3: Schematic depiction of the atmosphere with a horizontal temperature gradient. The red column (W) has a higher temperature than the blue column (C). The arrows represent air motions. The arrow in the red column represents rising air and that in the blue column represents sinking air, while the arrows across the two columns represent convergence or divergence of air between them.

recent studies have shown precipitation enhancement or its negligible variation with increasing aerosol particularly in a deep convective cloud or mesoscale convective systems (MCSs) [8, 9, 16, 22]. This is contrary to aerosol-induced precipitation suppression in the traditional understanding.

2.2. Instability. More studies need to be performed for the better understanding of the feedbacks among aerosol, microphysics, and dynamics in cloud systems. As a first step to the better understanding, these studies should put emphasis on the instability of environment in which cloud systems embed. This is because the instability determines the basic dynamic intensities of cloud systems and thus has a substantial impact on the feedbacks whose one of important components is cloud dynamics. One of most representative measures of the instability is convective available potential energy (CAPE). Studies over the last few years have shown that pollution or perturbation of aerosol (not acting as radiation absorbent but as cloud condensation nuclei) can make the air parcels warmer in an air column, which leads to an increase in CAPE [23–25]. This invigorates convection and enhances precipitation. However, the instability of the atmosphere can also be measured by the horizontal temperature gradient across more than one air column. This type of the instability measurement can be performed with mean available potential energy (MAPE). For instance, when there is local atmospheric heating or cooling, the horizontal temperature gradient occurs as seen in Figure 3. An air column with heating or a higher temperature tends to rise up, while an air column with cooling or a lower temperature tends to go down (Figure 3). To satisfy mass conservation, there is divergence of air from the air column with the higher temperature to that with the lower temperature at the upper parts of the air columns, while there is convergence of air from the air column with the lower temperature to that with the higher temperature at the lower parts of the air columns. These upward and downward motions, convergence, and divergence complete a circulation (Figure 3).

Most of recent studies on interactions between aerosol and the instability have been performed by using CAPE and these studies have been based on one air column and an isolated convective cloud in it (e.g., [24]). However, when it comes to the effect of aerosol on climate, we need to consider MCSs which are comprised of more than one cloud. This is because these MCSs serve as building blocks of the monsoon, the ITCZ, and the Hadley circulation that play important roles in global hydrologic and dynamic circulations and thus climate [4]. In the MCSs which are comprised of multiple clouds, it is hard to expect that all of clouds experience aerosol-induced convective invigoration. This is mainly due to competitions among clouds which occur at cloud scales. Recent studies have shown that, while CAPE for certain clouds increases, leading to their invigoration, other clouds experience decreases in their CAPE and dynamic intensity [12, 26–28]. This is because of more invigorated clouds "steal" humidity (or water vapor) and warm air as a source of an instability or CAPE from less invigorated clouds. More invigorated clouds have stronger updrafts and this induces stronger convergence around cloud bases to satisfy mass conservation. This stronger convergence brings humidity and warm air from less invigorated clouds to more invigorated clouds [29]. This leads to a situation where the size of more invigorated clouds further increases, while that of less invigorated clouds further diminishes and these clouds may disappear [12, 26–28]. This means that, with an increasing aerosol, cloud size distribution and cloud population change. Stated differently, with an increasing aerosol, MCSs experience changes in "cloud-system organization" represented by cloud size distribution and cloud population. In the next section, for the comprehensive understanding of the effects of aerosol on cloud-system organization, we need to gain a better understanding of MAPE as well as CAPE.

2.3. MAPE and Cloud-System Organization. Over a sufficiently long period of time and the globe, aerosol-induced changes in net precipitation are likely to be small, as precipitation must balance evaporation at the surface. Moreover, even in a MCS at a regional scale and a short period of time, while there is an increase in precipitation amount in more invigorated clouds, there is a decrease in precipitation amount in less invigorated clouds due to the abovementioned competitions among clouds. These increase and decrease offset each other, which leads to a very small aerosol-induced change in precipitation amount [9, 22, 30]. This demonstrates that we need to move our focus from precipitation amount to cloud-system organization and associated

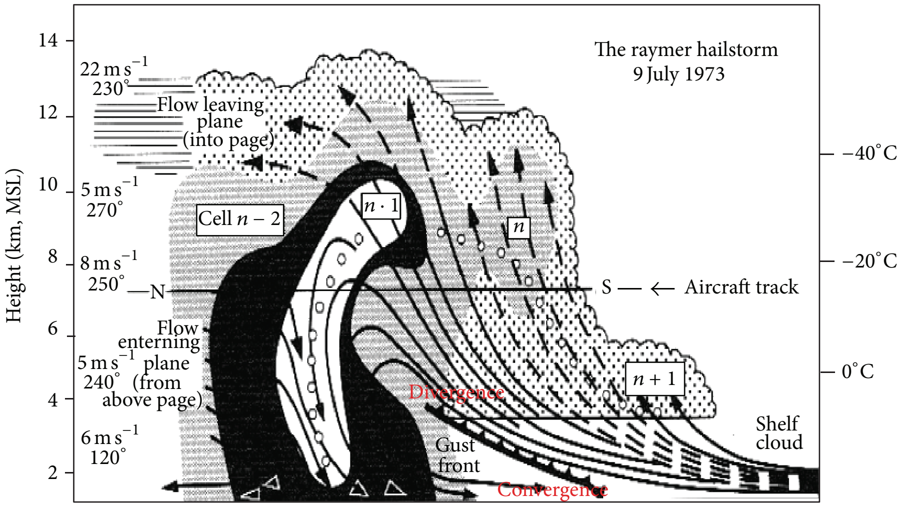

Figure 4: Schematic model of a supercell thunderstorm (from [4]). The solid and broken lines are streamlines of air flow relative to the moving system. Stippled, gray, and black shadings represent areas with low, medium, and high water content, respectively. The white area inside the black shading has the highest water content in the system. The thick line with triangular forms represents a gust front. The air in front of the gust front is warmer than the air behind the front and this leads to the development of updrafts in front of the front. The air behind the front is colder than that in front of the front due to evaporative cooling, which develops downdrafts. These updrafts and downdrafts are connected to each other to form a circulation through divergence of air (centering in the area with "Divergence") from the front part of the gust front to its back part and convergence of air (centering in the area with "Convergence") from the back part of the gust front to its front part.

spatiotemporal distributions of precipitation (or precipitation intensity), when it comes to aerosol-induced changes in precipitation properties. Supporting this, Li et al. [31] have demonstrated aerosol-induced changes in the distributions of precipitation using a 10-year observational data set.

The importance of aerosol-induced changes in cloud-system organization and spatiotemporal distributions of precipitation can be seen in the Sahel drought. The Sahel drought from 1960s to early 1980s was caused by none other than aerosol-induced changes in spatiotemporal distributions of precipitation and killed more than 100,000 people by inflicting famine on them [32]. In particular, altered precipitation distributions may have substantial impacts on the growth of rice that around 30 billion people in the Southeast and Northeast Asia take as staple food. Thus, studies for our better understanding of the effect of aerosol on cloud-system organization and associated precipitation distributions are imperative.

What is relation between the above-mentioned MAPE and cloud-system organization? To answer this question, first, let us look at individual clouds embedded in a MCS. Among phenomena in mesoscale cloud dynamics, gust front is well known. Gust front plays an important role in maintaining a MCS by inducing subsequent clouds [4]. Cold air or pools generated by a parent cloud collide with background warm air around the surface to form horizontal temperature gradient or gust front (Figure 4). In other words, this collision creates MAPE (which is closely linked to horizontal temperature gradient). Eventually, this gradient induces a circulation (due to the mechanism explained above) as seen in Figure 4. Updrafts which comprise the circulation and are located in the front of the gust front create subsequent or offspring clouds (Figure 4).

Recent studies have shown that an increase in aerosol concentration leads to increases in the mass of droplets as a source of evaporative cooling, in turn leading to increases in evaporation and the intensification of cold pools [5, 6, 12, 14, 30]. This intensified cold pools form a larger horizontal temperature gradient with background warm air or larger MAPE, which leads to a stronger circulation and associated updrafts around a gust front. Those studies have shown that these stronger updrafts generate more subsequent clouds and this intensifies competitions for convective energy or CAPE among clouds (e.g., [12]). The increasing competitions among clouds eventually induce a decrease in the size of the subsequently developing clouds and changes in precipitation distributions [30, 33]. Stated differently, aerosol-induced changes in MAPE alter cloud-system organization and associated spatiotemporal distributions of precipitation.

Let us look at the relation between MAPE and cloud-system organization at a scale larger than that of gust fronts. It is well known that there has been a substantial increase in aerosol concentration in metropolitan areas such as New York City and Los Angeles. However, in the suburban areas of these cities, the increase in aerosol concentration is not likely to be as large as that in the metropolitan areas. According to the mechanism explained above, with the larger increase in aerosol concentration, it is likely that there are more clouds and more associated condensational heating in the metropolitan areas than in the suburban areas. This means the formation of MAPE across the metropolitan and suburban areas. This formation of MAPE generates a circulation over the metropolitan and suburban areas with a scale much larger than the scale of gust fronts. Due to the additional release of condensational latent heat, the updraft part of the circulation is dominant over the metropolitan area, while the downdraft part of the circulation is dominant over the suburban area with colder air. To satisfy mass conservation, horizontal airflow eventually is formed between the metropolitan area and the suburban area as depicted in Figure 3; the warm red column and the cold blue column are equivalent to the metropolitan area and the suburban area, respectively, in Figure 3. The updrafts tend to intensify clouds over the metropolitan area and the downdrafts tend to weaken clouds over the suburban area. Eventually, precipitation enhancement can occur over the metropolitan area, while precipitation suppression is expected over the suburban area; note that, in the argument in this example, there is no consideration of background wind field; in other words, this argument is only about cloud-generated motions and aerosol impacts on them under an assumption that background wind does not exist or the influence of background wind is negligible. The updrafts can increase cloud population over the metropolitan area by nurturing clouds, while the downdrafts can decrease cloud population over the suburban area by suppressing clouds. Stated differently, the aerosol pollution in the metropolitan area affects the development of clouds and precipitation in the suburban area via the aerosol-induced circulation. This means that we need to consider much larger area than an area directly affected by aerosol pollution for the comprehensive understanding of aerosol-cloud interactions. Another important point we can draw from this is that, although aerosol-induced changes in total precipitation amount can be large for each of the metropolitan area and the suburban area, the offset between precipitation enhancement in the metropolitan area and precipitation suppression in the suburban area leads to small changes in the precipitation amount over the whole metropolitan and suburban areas.

3. Future Work

Aerosol-induced changes in cloud-system organization and spatiotemporal distribution of precipitation can be considered to be a by-product of an effort by a cloud system to reach a new equilibrium while minimizing changes in the overall property of the system, once an old equilibrium of heat distribution is perturbed by an external forcing. Here, the external forcing is aerosol pollution or perturbation. This type of effort is similar to a situation in a pond when we throw a stone at it. To disperse the pressure perturbation from an impact by the stone as a process of reaching a new equilibrium state of pressure, the pond generates ripples or gravity waves. As an effort to disperse aerosol-induced heat-energy perturbation (corresponding to the pressure perturbation in the pond) as a process of reaching a new equilibrium state of heat distribution, the cloud system develops circulations (corresponding to the ripples in the pond) and eventually cloud-system organization and precipitation distribution change. However, the total precipitation amount, which is one of the representations of the overall property of the system, would not change much. Here, we can raise an important question "what are the redistribution patterns of heat and precipitation when a system reaches an ultimate equilibrium state?" The answer to this question is important, since these redistributions of precipitation can constitute important factors which determine the distributions (regions or locations) of "flood," "drought," "hot air," and "cold air." These distributions have substantial social and economic consequences.

One of the best methodologies to answer the above mentioned question is to use models that can quantify the aerosol effect. However, aerosol-induced formation of circulations and associated compensation processes between clouds and between more and less polluted regions have not been simulated in traditional climate models adequately well. This is because these circulations, compensation processes, and associated changes in cloud-system organization and precipitation distributions are all related to subgrid cloud-scale processes that have not been resolved in those climate models. To resolve this issue, we can come up with a climate model which is able to resolve subgrid cloud processes. For example, due to a rapid development of computer capacity, climate models such as global cloud resolving model (GCRM) and superparameterization (SP) that resolve subgrid cloud processes are now in operation [34, 35]. However, due to a huge amount of computational cost GCRM and SP require, they have been used for simulations lasting only a few years or less. Hence, it is not that viable to gain meaningful climatic implications which we can get from simulations over a period of tens or hundreds of years by using GCRM and SP. Then, as an alternative, the traditional cloud parameterizations, not explicitly resolving the subgrid processes and thus requiring relatively a small amount of computational cost, can be utilized to examine aerosol-induced new equilibrium and associated retributions of heat and precipitation which occurs over a period of tens or hundreds of years. However, numerous previous studies have indicated that these traditional parameterizations have not been simulating the effect of the subgrid processes adequately well. Hence, it is imperative to further develop these parameterizations.

Subgrid cloud processes and their interactions with aerosol strongly depend on cloud types and their embedded environmental conditions such as instability, wind shear, and humidity [7, 8, 11, 12, 33, 36]. In particular, Fan et al. [36] and Lee [33] have shown that environmental or background humidity level basically determines interactions among aerosol, cloud evaporation, condensation, and moisture budgets in the vicinity of clouds. However, the traditional parameterizations have not been able to consider this dependence on humidity. Regarding the dependence on humidity, as discussed in Khain et al. [7], condensation and evaporation processes and aerosol impacts on them are not well represented in the traditional parameterizations, which leads to inaccurate assessment of the moisture budgets. Since subsequent clouds are affected by the moisture budgets, this in turn leads to inaccurate assessment of aerosol effects on the evolution of cloud systems and the overall dependence of the effects on humidity. The first step to improve the representation of subgrid processes in climate models is to consider the dependence on environmental conditions in the parameterizations. To consider the dependence on environmental conditions and particularly to improve the representation of the moisture budgets, we can perform intense observation campaigns utilizing instruments such as radars, aircrafts, and ground-based observation tools in a comprehensive way in regions such as East Asia where the level of understanding of aerosol-cloud interactions is very low, although the level of aerosol concentration is very high and thus it has been thought that the effect of aerosol on clouds is substantial. These campaigns are to identify mechanisms which control not only the dependence on environmental conditions but also the retributions of heat energy and precipitation induced by aerosol-cloud interactions over East Asia through observation and simulations of cases selected during the campaigns. Then, using the identified mechanisms, the parameterizations can be developed. In particular, comparisons among observation and simulations by bin and bulk models will provide a good opportunity to improve weaknesses (including the inaccurate representation of the moisture budgets) of bulk models (or bulk microphysics parameterizations) discussed in studies such as Fan et al. [37] and Khain et al. [7]. In addition to the representation of the moisture budgets, there are weaknesses associated with aerosol processing by clouds such as nucleation and impaction scavenging, chemical processes, and regeneration of aerosol by cloud-particle evaporation in bulk models. While some studies (e.g., [38]) have shown that scavenging processes have a substantial impact on aerosol-induced changes in cloud-system organization and associated precipitation distributions, the reverse has been true in other studies (e.g., [12, 39]). Harris et al. [40] have pointed out that models have not been simulating aerosol chemical processing by clouds such as sulfur dioxide oxidation. We need to resolve sources of these different arguments and chemical processing issues as a process of solving the weaknesses of bulk models through the intercomparison among bulk and bin models and observation, which is similar to work by Fridlind et al. [41].

For the reasonable identification of mechanisms which control not only the dependence on environmental conditions but also the retributions of heat energy and precipitation induced by aerosol-cloud interactions, it is important to separate the effect of aerosol on clouds from meteorological influences to assess the effect of aerosol on clouds with confidence. When aerosol effect is mixed with meteorological influences, it is hard to ascribe changes in cloud properties and, thus, in precipitation and radiation budgets solely to aerosol. Also, it is hard to grant confidence to parameterizations for aerosol-cloud interactions, developed based on observed data where aerosol effects mingle with meteorological influences. As discussed in Stevens and Feingold [42], a separation of meteorological influences from aerosol effect in observed data is not easy due to the buffering processes. However, if we utilize modeling work, it is viable to perform the separation. This enables us to understand the buffering mechanism and its impact on aerosol-cloud interactions more clearly. This also enables us to evaluate how really large aerosol effects are as compared to meteorological variations. For this, integration between observation and modeling studies is necessary. Observed meteorological and aerosol conditions in East Asia can be imposed on model simulations. Then, as done in Lee and Penner [43], sensitivity tests can be performed for the separation. First, sensitivity simulations can be performed with a variation of aerosol but with fixed meteorological conditions. Then, sensitivity simulations can be repeated with a fixed aerosol but with a variation of meteorological conditions as in Lee and Penner [43]. A comparison among these simulations identifies the effects of aerosol on clouds, which are separated from meteorological influences.

The above-described processes are expected to enhance our understanding of subgrid aerosol-cloud interactions significantly (considering the low-level understanding of aerosol-cloud interactions in East Asia) and thus to develop a much better representation of subgrid cloud processes and their interactions with aerosol in climate models. Through a comparison between these identified mechanisms in East Asia and mechanisms from other regions, we are able to develop more general and comprehensive parameterizations which can be applied to various environmental conditions and cloud types with minimized tuning of parameters. This development contributes to a better and more general representation of the subgrid aerosol-cloud interactions, associated formation of circulations, compensation or competitions among clouds and cloud processes, and retributions of heat and precipitation in climate models. Although studies on the effects of aerosol on clouds and climate have been going on over the last decades, uncertainties in the prediction of climate change by aerosol-cloud interactions are still very high [3]. However, the above-mentioned intense observation campaigns and associated development of parameterizations can make a significant contribution to the reduction of the uncertainties and thus to providing more confident information on climate change to society.

Conflict of Interests

The authors do not have any conflict of interests with the content of the paper.

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