A numerical study of aerosol regeneration effect using WRF coupled with a bin microphysics scheme

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Introduction

Atmospheric aerosols working as cloud condensation nuclei (CCN) and ice nuclei (IN) affect cloud macrophysical and microphysical properties, further influence precipitation types and amount, and eventually impact the climate system through the interactions between clouds and precipitation. On the other hand, aerosols are modulated by clouds and precipitation. Processed and transported by clouds, aerosols are redistributed in the air through scavenging (sink) and evaporation (source). These redistributed and modified aerosols affect cloud and precipitation and their subsequent developments (Wurzler et al. 2000). The problem of how changes in cloud, precipitation, and dynamics are attributed to perturbations in aerosol properties has been extensively studied. In contrast, the extent to which changes in clouds, precipitation and dynamics regulate aerosols has not yet been studied closely. Pruppacher and Jaenicke (1995) estimated that clouds evaporate five times before they precipitate globally. Hence, these evaporating clouds release significant amount of aerosols comparable to those generated by oceans and deserts, which should affect clouds and precipitation. Although some studies (e.g., Yin et al. 2005, Engstorm et al. 2008) investigated how aerosols are released by evaporated drops and their effect on primary cloud and precipitation, no systematic sensitivity study has been conducted for different regeneration methods or for different cloud types. This research performed a sensitivity study on how cloud-processed aerosol affect primary and secondary cloud and precipitation for orographic cloud case.

Methodology

To tackle the problem of how regenerated aerosols affect clouds and precipitation, numerical representations of aerosols activation and their regeneration by clouds are required. A mixed phase bin microphysics scheme (Rasmussen et al. 2002) has been coupled into the Weather Research and Forecast model (WRF) (Fig. 1). A modified aerosol activation scheme based on Kohler theory (Yin et al. 2000) has been adopted in this coupled model to account for the effect of aerosol size distribution on the initiation of cloud droplets. A single log-normal size distribution of aerosol regeneration mechanism based on droplet-aerosol one-to-one relation (Mitra et al. 1992) has been implemented in the model as well.

Mixed phase detailed bin scheme

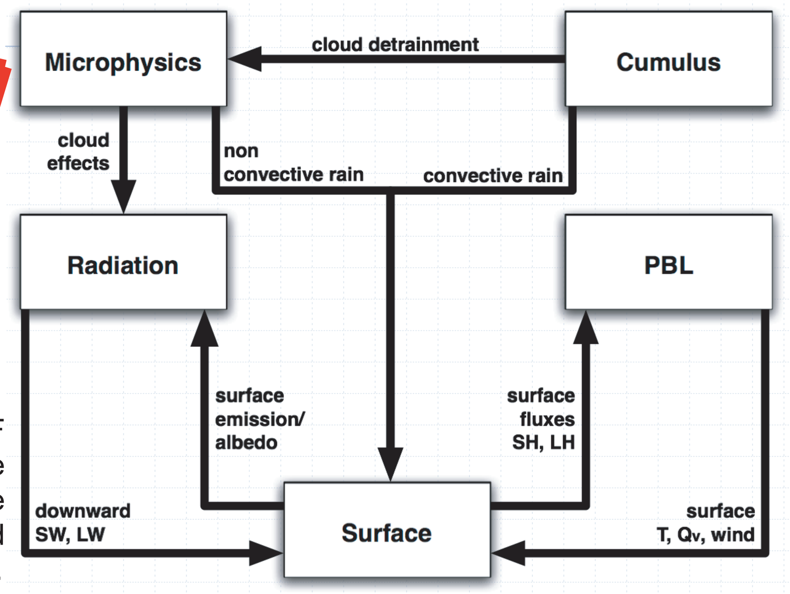

Figure 1. Interaction of WRF physics parameterizations. The original microphysics scheme has been replaced by the mixed phase bin microphysics scheme.

Experiments and Results

In this study, a series of sensitivity simulations have been carried out to investigate how regenerated aerosols affect cloud/precipitation for orographic mixed phase stratiform cloud using the coupled model. The simulation domain is a two dimensional grid (x-z) covering 1000 km in the horizontal and 23 km in the vertical. The horizontal resolution is 2 km. A terrain following vertical coordinate is used with 60 layers spaced between 20 m in the lowermost and 1400 m in the uppermost layer. The time step is 10s for the dynamics and 2s for the condensation process. There are two bell-shaped mountains with peaks locating at 360 and 640 km. The heights are 800m and half-widths are 20 km (Fig. 2). The dynamical initialization is followed the setup of Muhlbauer and Lohmann (2008) except that the surface temperature is 280K here. The initial aerosol distributions are prescribed as clean and polluted respectively to test the sensitivity in two extreme cases (Fig. 3). One run without aerosol regeneration and six runs with different mean radii (0.01, 0.05, 0.1, 0.5, 1 and 5 um) of regenerated aerosols have been conducted. In order to reach steady state, each simulation is run for 10 hours.

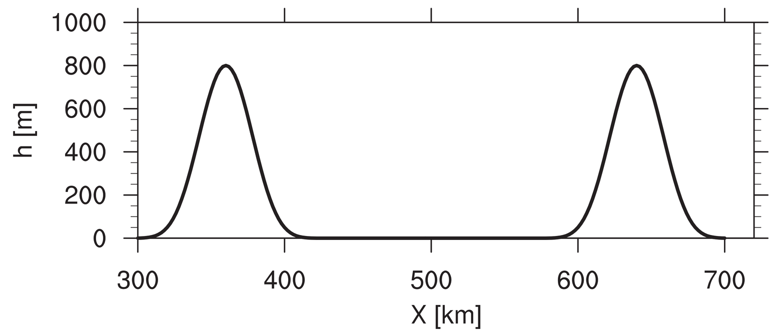

Figure 2. Two bell-shaped mountians in the domain.

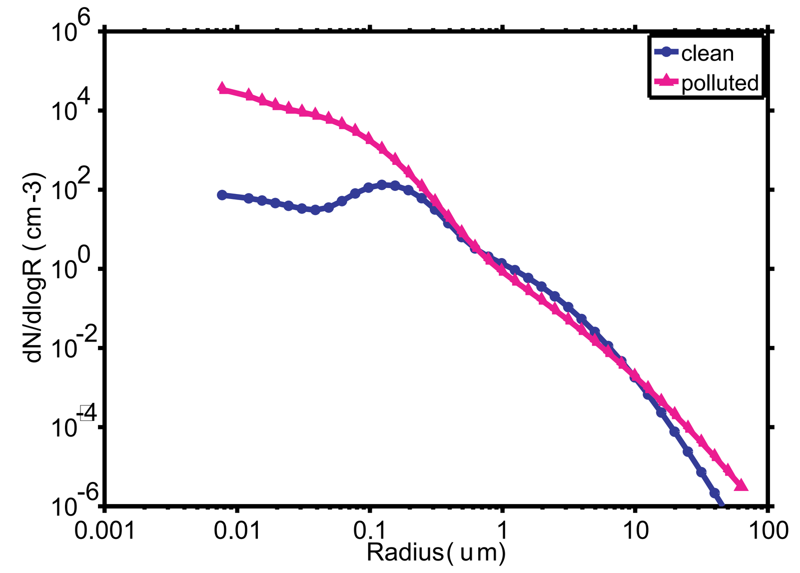

Figure 3. Initial aerosol distributions

The results showed that when the regeneration of log-normal distributed aerosols is considered in an orographic cloud, the primary and secondary cloud/precipitation respond to aerosol loading in non-monotonic ways. For both clean and polluted cases, as their mean radii increase the regenerated aerosols suppress rainfall at first and then invigorate it after the aerosol size reaches a certain threshold (Fig. 4). This effect is especially prominent for secondary clouds. Compared to the nonregeration run, only large regenerated aerosols significantly decrease (increase) maximum cloud (rain) water mixing ratios in the first 4 hours and small sizes reduce maximum rain water more than large sizes do in the later stage of the simulation (Fig. 5A and C). For polluted case, large sizes have stronger perturbations in maximum cloud water than small ones during the entire simulation and all sizes of aerosols affect rain water mainly after the 5th hour (Fig. 5B and D).

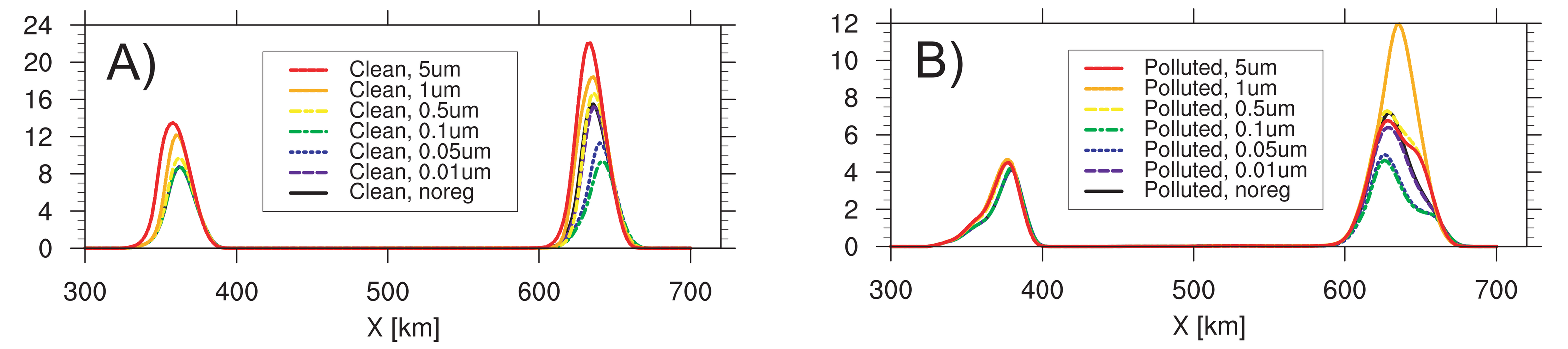

Figure 4. Ground rainfall distribution (mm) at the end of each simulations. A) clean case. B) polluted case

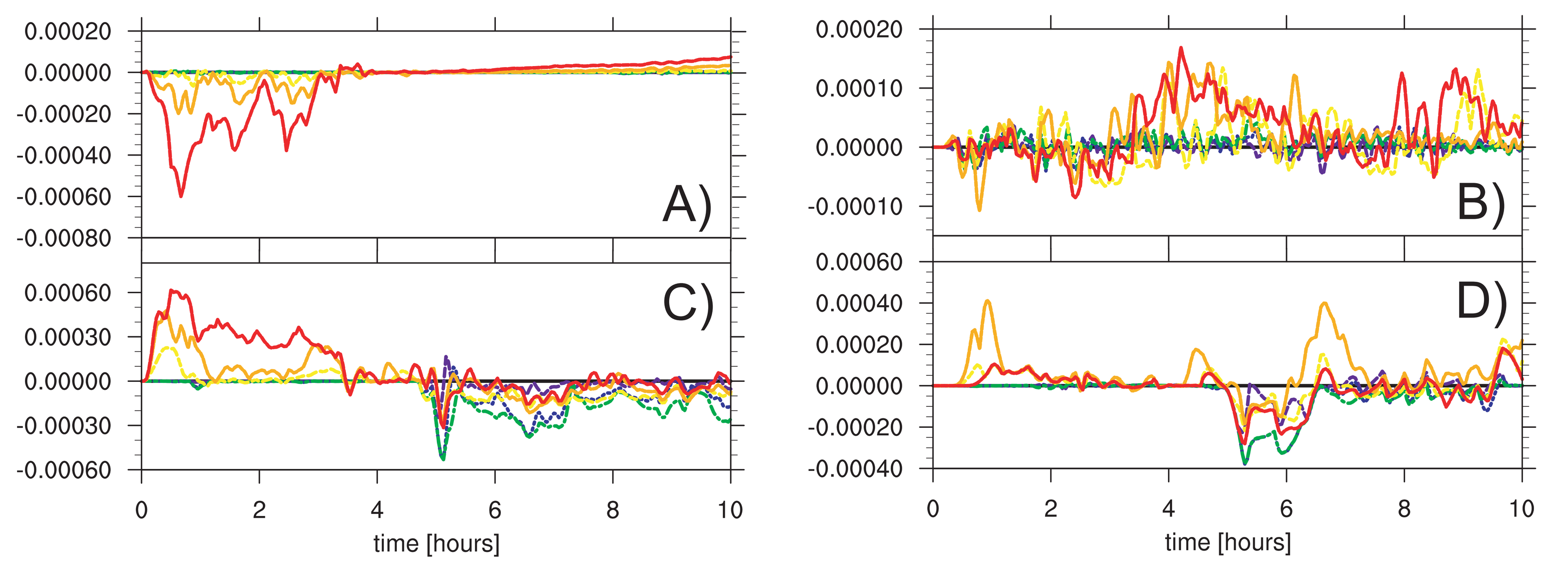

Figure 5. Time series of differences of maximum cloud water mixing ratio (kg/kg) between regeneration and nonregeneration runs for A) clean case and B) polluted case, and rain water mixing ratio (kg/kg) for C) clean case and D) polluted case.

An examination of the water-related microphysical processes reveals that regenerated aerosols affect cloud and precipitation through similar routes in these two scenarios. Firstly, both cases have their water content produced mainly by condensation on CCN (Fig. 6A and B). It is obvious that when regenerated aerosols are released into the air, more water condense on these extra CCN than in the nonregeneration case. However, the production of water from condensation on CCN is almost balanced by the evaporation of cloud drops (Fig. 6C and D). Smaller sizes tend to have more evaporation than condensation on CCN. Secondly, for both cases smaller sizes reduced the efficiency of ice-water coagulation while larger ones increase it overall (Fig. 6E and E). Consequently, these water uptakes by ice introduced the secondary water production from melting (Fig. 6G and H). Figure 7 illustrates that regenerated aerosols enhance the collision-coalescence process in both cases. When the size is small, these regenerated aerosols only silghtly increase it in later stage. Large size aerosols significantly increase the process in the early stage for the clean case and in the later stage for the polluted case.

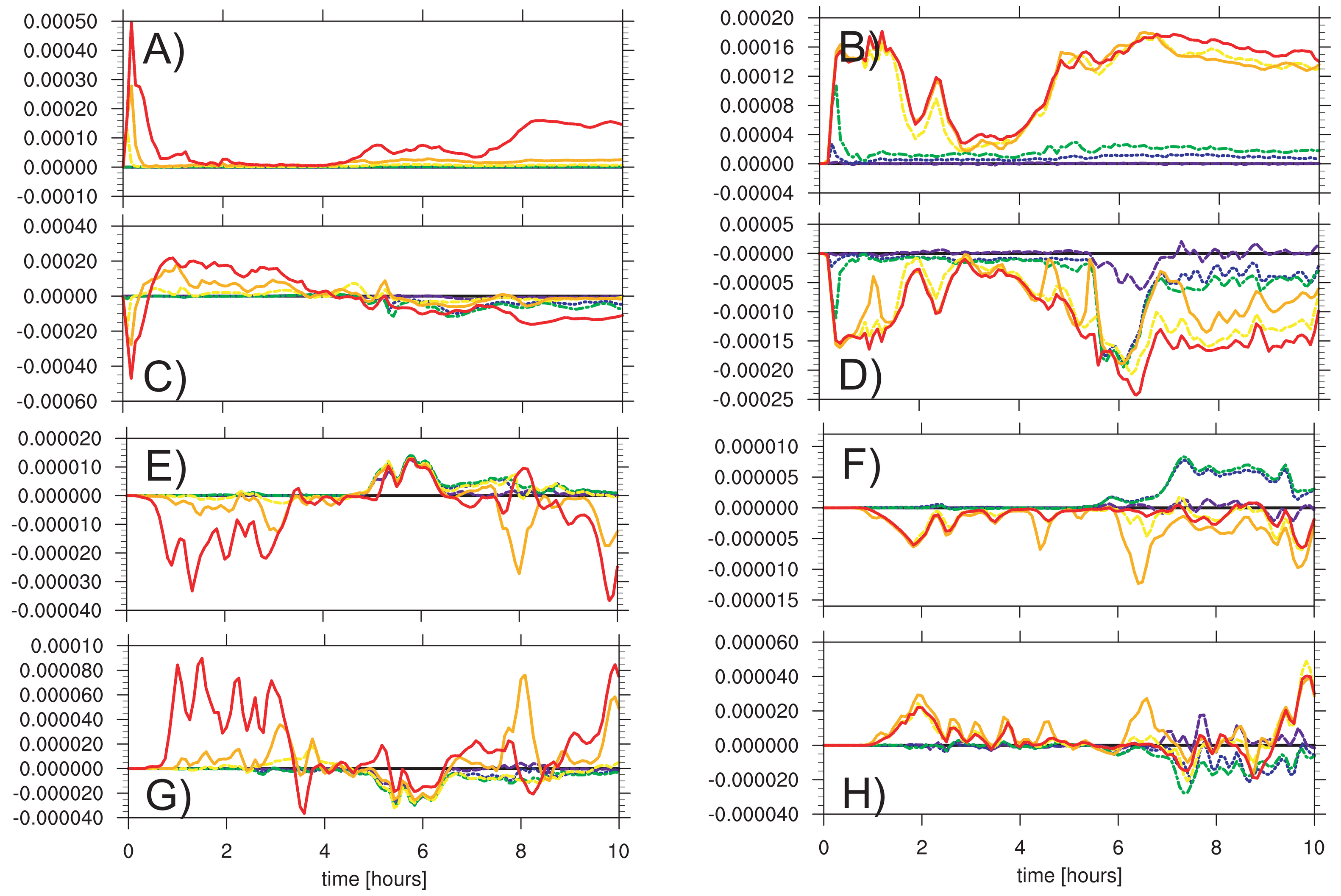

Figure 6. Time series of differeces of domain total condesation rate on CCN (A,B), condensation or evaporation rate on drops (C,D), ice-water coagulation rate (E,F) and melting rate (G,H) between regeneration and nonregeneration runs. All plots unit in kg/kg/s. Left panels for clean case and right panels for polluted case.

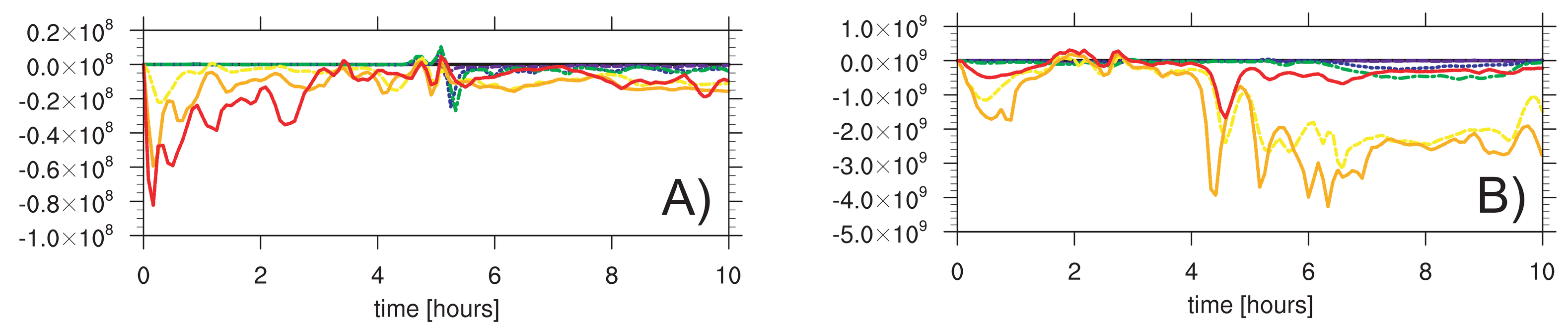

Figure 7. Time series of differeces of domain total drop concentration changing rate by collision-coalescence (#/kg/s) for A) clean case and B) polluted case

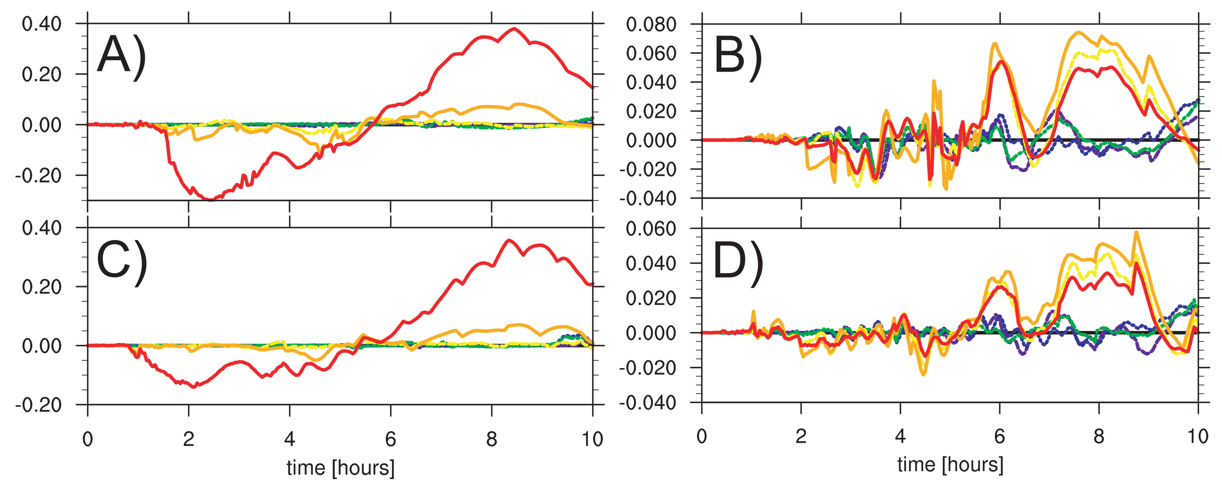

Figure 8. Time series of differeces of domain maximum horizontal wind (m/s) for A) clean case and B) polluted case and veritical wind for C) clean case and D) polluted case.

The dynamic feedbacks of the interaction between the regenerated aerosols and the cloud are plotted in figure 8. For the clean case, small regenerated aerosols hardly modify the dynamics but large ones reduce the kinetic energy at first and increase it later (Fig. 8A and C). For the polluted case, large sizes mainly invigorate the dynamics in the late stage of simulatoins while small ones have slight effect on the dynamics (Fig. 8B and D). The dynamic feedbacks of large regenerated aerosols in the clean case are about one order of magnitude greater than those in the polluted case.

Summary

The effect of regenerated aerosols on cloud and precipitation is a "commonly missing ring" in current studies on the feedback chain of aerosol, cloud, precipitation and climate interactions. This study is a first attempt to quantify how the size distribution of regenerated aerosols affect cloud and precipitation in a stably stratified orographic cloud case. The results showed that small regenerated aerosols (r < 0.5 um) suppress precipitation by reducing the water uptakes by ice particles. On the other hand, large regenerated aerosols enhance precipitation by condensing more water on them and by increasing the water uptakes by ice. The different onsets of collision-coalescence process between clean and polluted cases may explain the ground rainfall difference from the primary clouds. In this study, the dynamic feedbacks of these regenerated aerosols are not as important as their microphysical feedbacks. To further investigate the effects of regenerated aerosols on cloud and precipitation, more simulations for different cloud types are needed. At the same time, field experiments should be carried out to directly measure the concentration, size distribution of the regenerated cloud-processed aerosols.

The coupled model can be used to investigate scientific problems such as fog formation and can also be applied to real-world applications such as artificial weather modification.

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