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Quantifying the importance of galactic cosmic rays in cloud microphysical processes

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A B S T R A C T

Galactic Cosmic Rays are one of the major sources of ion production in the troposphere and stratosphere. Recent studies have shown that ions form electrically charged clusters which may grow to become cloud droplets. Aerosol particles charge by the attachment of ions and electrons. The collision efficiency between a particle and a water droplet increases, if the particle is electrically charged, and thus aerosol-cloud interactions can be enhanced. Because these microphysical processes may change radiative properties of cloud and impact Earth's climate it is important to evaluate these processes' quantitative effects. Five different models developed independently have been coupled to investigate this. The first model estimates cloud height from dew point temperature and the temperature profile. The second model simulates the cloud droplet growth from aerosol particles using the cloud parcel concept. In the third model, the scavenging rate of the aerosol particles is calculated using the collision efficiency between charged particles and droplets. The fourth model calculates electric field and charge distribution on water droplets and aerosols within cloud. The fifth model simulates the global electric circuit (GEC), which computes the conductivity and ionic concentration in the atmosphere in altitude range 0–45 km. The first four models are initially coupled to calculate the height of cloud, boundary condition of cloud, followed by growth of droplets, charge distribution calculation on aerosols and cloud droplets and finally scavenging. These models are incorporated with the GEC model. The simulations are verified with experimental data of charged aerosol for various altitudes. Our calculations showed an effect of aerosol charging on the CCN concentration within the cloud, due to charging of aerosols increase the scavenging of particles in the size range 0.1 μm to 1 μm.

1. Introduction

Water vapor is an important, but variable, atmospheric constituent, and Earth's water cycle is mostly dependent on the formation and condensation of clouds. Small variations in cloud have the potential to influence the climate, therefore the suggestions that there are effects of galactic cosmic rays (GCR) on clouds (Hiremath, 2006; Gray et al., 2010) raise the question of how large the effects would be for the climate system. The GCR varies on many timescales, and, notably, with the Schwabe cycle of solar activity. Ion production in the lower and middle atmosphere is mostly governed by the GCR flux (Bazilevskaya et al., 2008) except very close to the surface of Earth, where surface release of radon also contributes. Particles on which clouds form-so called cloud condensation nuclei (CCN)—have been suggested to show, in some circumstances, sensitivity to ion production rates (Carslaw et al., 2002) as studies have shown that ions can form aerosols (Kulmala et al., 2004; Kirkby et al., 2011). If alternatively or additionally, CCN become electrically charged, the collision efficiency between a particle and a water droplet increases, which enhances aerosol-cloud interaction rates (Tripathi et al., 2006). Formation and growth of droplet from water vapor is directly related to supersaturation vapor pressure and distribution of particles within the cloud (Nenes et al., 2001). A cloud microphysical model has been developed, which includes electrically-influenced processes (Rycroft et al., 2012; Harrison and Ambaum 2008) and then coupled with a Global Electric Circuit (GEC) model. This coupled model was then used to study the correlation of GCR variation during the solar cycle to CCN concentration and the subsequent droplet distribution.

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Five major models are included in the coupled simulation, which are (i) The prediction of cloud base, (ii)growth of cloud droplets, (iii) scavenging of particles within the cloud, (iv) electrical model within the cloud, and (v) GEC. One method for simulation of droplet growth and distribution in non-precipitating clouds is a cloud parcel model, which considers the conservation of heat and moisture within the parcel and predicts growth of aerosols to CCN (Nenes et al., 2001; Seinfeld and Pandis, 2006). When a rising air parcel reaches the level of supersaturation, water vapor starts to condense on the CCN present. The CCN arise from the background aerosol present; the subsequent microphysical processes such as condensation/coagulation growth, breakup, and evaporation decide the droplet distribution.

Droplets undergo gravitational settling in clouds. Aerosols have negligible settling velocities compared to droplets, because of their smaller size (mass) and greater upward forces. Droplets capture aerosols during collisions causing removal of aerosol from clouds. The fraction of particles colliding with drop is termed as collision efficiency. Studies have found relatively greater collision efficiency for fine and coarse mode aerosols due to Brownian forces and inertial forces, respectively; but very low collision efficiency in accumulation mode (0.1–2.5 μm particle size). This region of low collision efficiency has long been known as the Greenfield gap (Greenfield, 1957), but recent studies have shown that inclusion of electrical effects significantly increase the collisions efficiency so as to fill in the Greenfield gap (Tinsley et al., 2000, 2006; Tripathi et al., 2006; Zhou et al., 2009). These considerations have been implemented in the particle scavenging model.

Charges on aerosols can affect CCN and Ice Forming Nuclei (IFN) concentrations in the cloud (Tripathi and Harrison, 2001; 2002; Kanawade and Tripathi, 2006). It is therefore important to know the charge distribution of aerosols and droplets within the cloud. The vertical electric field within the cloud also plays a crucial role in charging process, as it establishes vertical motion of ions from one layer to other. Accumulation of opposite charges at the upper and lower edges of layer clouds has been confirmed (Nicoll and Harrison, 2010). Several numerical models have been developed to calculate the electric field, ion concentration, and aerosol charge distribution within clouds (e.g. Zhou and Tinsley, 2007; Srivastava and Tripathi, 2010).

Atmospheric air, due to the presence of small ions generated by cosmic rays, is always slightly electrically conductive. These small ions are highly mobile and can be accelerated easily under the existing electric field in the atmosphere. The magnitude electric field present in atmosphere varies from 100 Vm^{-1} in fair weather to 10,000 Vm^{-1} in thunderstorm (MacGorman and Rust, 1998). The global electric circuit is a combination of the upward current during thunderstorms and a very small compensating downward electric current during fair weather conditions (Harrison, 2000). For an aerosol-free atmosphere this field is small but can have certain impact on microphysical properties of clouds.

Models have been developed dealing with growth of droplets in the cloud (Nenes et al., 2001), collision efficiency of charged aerosol (Tinsley et al., 2006), and charging of aerosols in clouds (Zhou and Tinsley, 2007). All these models used mono-disperse distribution of aerosols and single charge on the particles. In the present work poly-disperse distribution of aerosols with multiple charge on the particles have been used, which is a more realistic scenario. For the first time, all these modeling approaches have been coupled together to study the effect of the variation of GCRs from solar minimum to maximum on cloud drop formation in stratiform clouds.

2. Model description

An integrated numerical model system has been designed to link aerosol charging, CCN formation, cloud growth, particle scavenging in the cloud, and GEC. This model is built from five different numerical models (given in Sections 2.1 to 2.5), coupled together. The flow diagram of the coupled model is provided in Fig. 1.

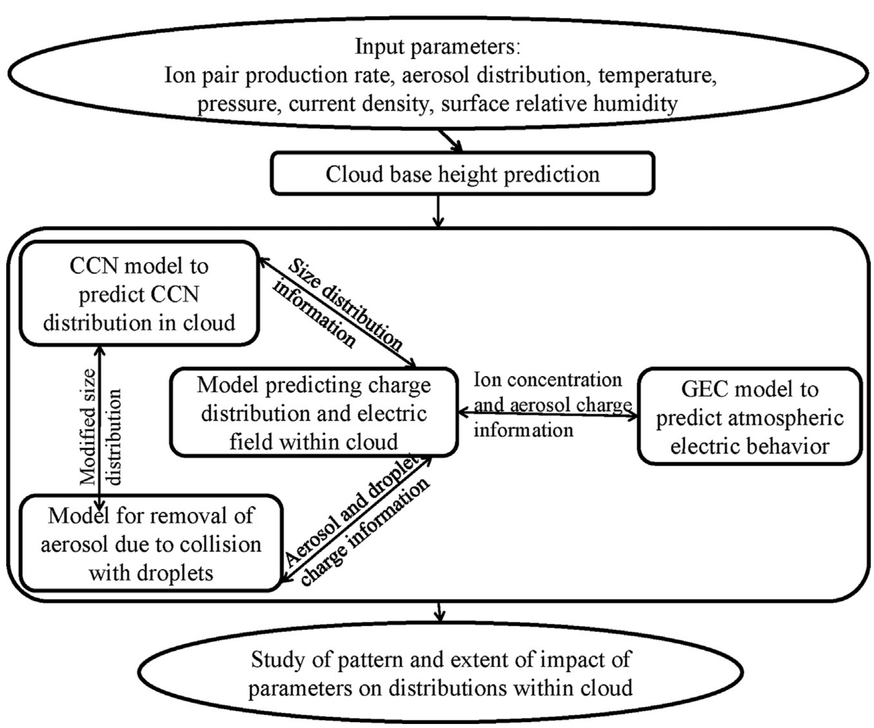

Fig. 1. Schematic diagram of different processes simulated by the coupled model approach adopted.