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Effects of drop freezing on microphysics of an ascending cloud parcel under biomass burning conditions

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Abstract

There is some evidence that the initiation of warm rain is suppressed in clouds over regions with vegetation fires. Thus, the ice phase becomes important as another possibility to initiate precipitation. Numerical simulations were performed to investigate heterogeneous drop freezing for a biomass-burning situation. An air parcel model with a sectional two-dimensional description of the cloud microphysics was employed with parameterizations for immersion and contact freezing which consider the different ice nucleating efficiencies of various ice nuclei. Three scenarios were simulated resulting to mixed-phase or completely glaciated clouds. According to the high insoluble fraction of the biomass-burning particles drop freezing via immersion and contact modes was very efficient. The preferential freezing of large drops followed by riming (i.e. the deposition of liquid drops on ice particles) and the evaporation of the liquid drops (Bergeron–Findeisen process) caused a further decrease of the liquid drops' effective radius in higher altitudes. In turn ice particle sizes increased so that they could serve as germs for graupel or hailstone formation. The effects of ice initiation on the vertical cloud dynamics were fairly significant leading to a development of the cloud to much higher altitudes than in a warm cloud without ice formation.

Keywords: Biomass burning; Heterogeneous drop freezing; Ice nuclei; Mixed-phase cloud

1. Introduction

Biomass burning is one of the main sources of atmospheric aerosol particles (Levine, 1991). The fire induced convection transfers soils from the ground as well as burned and unburned vegetation fragments into the atmosphere. Field measurements indicate that particles from biomass burning consist of biogenic, pyrogenic, and soil dust components with a high insoluble fraction between 80% and 95% (Artaxo et al., 1998; Feingold et al., 2001, Guyon et al., 2003). The number size distributions of these particles show large amounts of small particles (Helsper et al., 1980; Reid et al., 1998). Such particle distributions ingested in clouds lead to the formation of a large number of small drops. Thus, biomass burning can cause the suppression of warm rain as the formation of precipitation from these small drops by collision and coalescence is hardly possible (Rosenfeld, 1999; Andreae et al., 2004). However, another way to form precipitation is the ice phase.

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In a temperature range between 0 and $-35\,^{\circ}$C primary ice in clouds is mostly formed by heterogeneous freezing, i.e. by particles containing an insoluble residue or consisting completely of insoluble material. Owing to their composition these ice nuclei initiate freezing at significantly different temperatures, leading to the formation of mixed phase clouds. An important way to form ice particles heterogeneously in the atmosphere is the freezing of super-cooled drops in immersion and contact modes (Pruppacher and Klett, 1997). For heterogeneous initiation of the ice phase the preconditions are fairly good in biomass burning clouds: The very high insoluble fraction of biomass burning particles potentially enhances ice formation (Diehl et al., 2006), and it contains particles which are known as efficient ice nuclei, i.e. black carbon, minerals, and biological particles (Artaxo et al., 1998; Guyon et al., 2003). On the other hand, both immersion and contact freezing show a preferential freezing of large drops (Diehl and Wurzler, 2004; Diehl et al., 2006). Thus, important questions are if under biomass burning conditions freezing of super-cooled drops occurs, if it is sufficient to affect the vertical cloud dynamics, and if precipitation-sized ice particles could form. In the present simulations, drop formation in clouds under biomass burning conditions was compared to activation of various aerosol particle number size distributions in clouds under cleaner conditions. Ice formation in the biomass burning clouds was simulated considering the portioning of the particles and their ice nucleating efficiency. A sectional cloud model with a detailed two-dimensional description of warm and cold microphysics was employed (Simmel and Wurzler, 2006; Diehl et al., 2006).

2. Model description

For the present simulations an adiabatic air parcel model with entrainment (Flossmann et al., 1985; Pruppacher and Klett, 1997) was employed. An air parcel model describes a rising bubble of air whose radius increases with height. Dry air is mixed with moist air into the parcel through entrainment. The advantage of an air parcel model is that all changes in the microphysical evolution of the cloud can be attributed to microphysical processes. On the other hand, this can only be achieved for a tradeoff in cloud dynamics including some well-known weaknesses in the treatment of precipitation sized cloud particles which stay inside the parcel. However, for the present case of biomass burning cloud drops typically remain rather small. Therefore, the more important limiting factor is the rather simple cloud dynamics.

The employed model includes warm and cold cloud microphysics and the interactions between aerosol particles and hydrometeors (Simmel and Wurzler, 2006; Diehl et al., 2006). The aerosol particles are internally mixed with variable insoluble and soluble fractions. The sectional description of cloud microphysics includes a number of warm microphysical processes such as growth and shrinking of aerosol particles by water vapor diffusion, impaction scavenging, drop nucleation, growth, evaporation, collision and coalescence. A state-of-the-art iterative condensation scheme is implemented. The entrainment of aerosol particles, drops, ice particles, temperature, and humidity is embedded (Simmel et al., 2005). The cold microphysics includes the freezing of drops in immersion and contact modes as primary freezing processes (Diehl and Wurzler, 2004; Diehl et al., 2006). Both descriptions for immersion and contact freezing consider the ice nucleation efficiency of different particle types. Condensation freezing is included implicitly in immersion freezing as drops which are nucleated during the ascent of the air parcel by entrained aerosol particles could freeze immediately by immersion freezing. Deposition freezing, i.e. ice nucleation directly from the vapour phase, and homogeneous freezing of super-cooled drops are both neglected in the present model simulations because heterogeneous freezing via immersion, condensation, and contact modes are the dominant freezing processes for the present situation of biomass burning with a large amount of potential ice nuclei. Deposition freezing takes place at lower temperatures than the other heterogeneous freezing processes, homogeneous freezing at significantly lower temperatures than all heterogeneous freezing processes (Schaller and Fukuta, 1979; Koop et al., 1999).

In the immersion mode, the freezing rate for pure water drops of same sizes containing insoluble particles is given by

$$-\frac{\mathrm{d}N_\mathrm{f}}{\mathrm{d}t} = N_\mathrm{u} a B_{h,i} V_\mathrm{d} \exp(-aT)\frac{\mathrm{d}T}{\mathrm{d}t}, \tag{1}$$

where N_f is the number of frozen drops, N_u the number of unfrozen drops, V_d the drop volume in cm^3, T the temperature in $^{\circ}$C, a and $B_{h,i}$ constants with $a = 1\,^{\circ}\mathrm{C}^{-1}$. The constant $B_{h,i}$ in cm^{-3} stands