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A glaciation indirect aerosol effect in a statistical analysis of modeled mixed-phase orographic precipitation over the Alps

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Aerosols act as cloud condensation or ice nuclei, altering the microphysical properties of clouds and hydrometeors. Increasing the aerosol number in warm-phase clouds is thought to cause a decrease in the rate of rain formation, whereas the physical processes that affect a mixed-phase cloud and precipitation particles such as ice-crystals, graupel and snowflakes, are more uncertain. Recent studies have shown that increasing number concentrations of soluble aerosols may also reduce the riming efficiency and therefore decrease precipitation. On the other hand, the glaciation of a cloud due to heterogeneous freezing of cloud droplets may enhance the formation of graupel and snow.

Using a numerical weather prediction model coupled to a 2-moment cloud and aerosol microphysics at a horizontal resolution of 2.2 km, we show in a statistical framework with 310 2D-simulations of mixed-phase orographic precipitation over complex terrain that the presence of the ice-phase determines the magnitude and the sign of the effect of an increasing aerosol number concentration on orographic precipitation. We show that this indirect aerosol effect is much less pronounced in cold simulations compared to a warmer subset, and that cloud glaciation tends to compensate and even overcome the loss of rain in polluted situations. Comparing the simulated pairs of clean and polluted cases, we find a reduction of rain by 23% on average (range of relative differences: -60% to 0%) in the polluted cases due to the decline of autoconversion and accretion rates. In the cold subset of our simulations, a much broader range of differences (standard deviation: 64%) and a tendency toward increasing precipitation (mean: +17%) in the polluted cases is found through enhanced ice-microphysical processes such as riming and aggregation of graupel and snow, respectively. Furthermore, our study shows that in comparison with the clean cases approximately 3.5-5% more precipitation spills over to the leeward side of the mountains in the polluted cases as a consequence of the deceleration of precipitation formation.