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A review of our understanding of the aerosol–cloud interaction from the perspective of a bin resolved cloud scale modelling

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ABSTRACT

This review compiles the main results obtained using a mesoscale cloud model with bin resolved cloud micophysics and aerosol particle scavenging, as developed by our group over the years and applied to the simulation of shallow and deep convective clouds. The main features of the model are reviewed in different dynamical frameworks covering parcel model dynamics, as well as 1.5D, 2D and 3D dynamics. The main findings are summarized to yield a digested presentation which completes the general understanding of cloud–aerosol interaction, as currently available from textbook knowledge. Furthermore, it should provide support for general cloud model development, as it will suggest potentially minor processes that might be neglected with respect to more important ones and can support development of parameterizations for air quality, chemical transport and climate models.

Our work has shown that in order to analyse dedicated campaign results, the supersaturation field and the complex dynamics of the specific clouds needs to be reproduced. Only 3D dynamics represents the variation of the supersaturation over the entire cloud, the continuous nucleation and deactivation of hydrometeors, and the dependence upon initial particle size distribution and solubility.

However, general statements on certain processes can be obtained also by simpler dynamics. In particular, we found:

> Nucleation incorporates about 90% of the initial aerosol particle mass inside the cloud drops. Collision and coalescence redistributes the scavenged aerosol particle mass in such a way that the particle mass follows the main water mass. Small drops are more polluted than larger ones, as pollutant mass mixing ratio decreases with drops size. Collision and coalescence mixes the chemical composition of the generated drops. Their complete evaporation will release processed particles that are mostly larger and more hygroscopic than the initial particles. An interstitial aerosol is left unactivated between the cloud drops which is reduced in number and almost devoid of large particles. Consequently, impaction scavenging can probably be neglected inside clouds. Below clouds, impaction scavenging contributes around 30% to the particle mass reaching the ground by a rainfall event. The exact amount depends on the precise case studied. Nucleation and impaction scavenging directly by the ice phase in mixed phase clouds seems to play a minor role with respect to the particle mass that enters the ice particles via freezing of the liquid phase. The aerosol scavenging efficiency generally follows rather closely the precipitation scavenging value. The nucleation scavenging efficiency is around 90% for the liquid phase clouds and impaction scavenging generally contributed to about 30% of the particle mass in the rain. Clouds are very efficient in pumping up the boundary layer aerosol which essentially determines the cloud properties. For a marine case studied the net pumping depleted about 70% of the aerosol from the section of the boundary layer considered. The

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larger particles (and thus 70% of the mass vented up) got activated inside the cloud. A weak net import through cloud top and the upwind side was found, as well as a larger net export at the downwind side. The outside cloud subsidence can add to the replenishment of the boundary layer and eventually cause a recycling of the particles into the cloud.

The results of the parcel model studies seem to indicate that increasing particulate pollution and decreasing solubility suppresses rain formation. In individual and short time cloud simulations this behaviour was even confirmed in our 3D model studies. However, taking into account entire cloud fields over longer periods of time yields the strong spatial and temporal variability of the results with isolated regions of inverse correlation of the effects. Even though in general initially the expected behaviour was found, after several hours of simulation, the overall precipitation amounts of the more polluted cases caught up. This suggests that a changing pollution will affect the spatial and temporal pattern of precipitation, but will probably not reduce the overall long term precipitation amount which might be entirely governed by the moisture state of the atmosphere. Our results regarding mixed phase precipitation with respect to "all liquid" cases seem to confirm this idea, as with increasing modelling time the precipitation mass of both cases also become similar.

1. Introduction

Still in the 1970s, the community of the cloud physicists was well separated from the community of the aerosol physicists. It was commonly understood that clouds were determined by the sounding and water vapour supply and that saturation was mostly maintained. Aerosol particles were mainly related to health problems.

However, even at that time the role of particles in cloud nucleation was known already for about a hundred years from scientists like Aitken and Wilson (for a review see Pruppacher and Klett, 1997). But first attempts of planned weather modification to make use of this knowledge were only started in the middle of the 50s. In particular the role of silver iodide on the formation of the ice phase was used for hail prevention (see Cotton and Pielke, 1992 for a review of cloud seeding). Then, with environmental problems such as acid rain and political scenarios such as nuclear winter (see also Cotton and Pielke, 1992), the interest in the coupling of pollution and clouds grew.

Hans Pruppacher was among the first to study extensively the interaction of aerosol particles and cloud hydrometeors, and he conducted pioneering work in a wind tunnel to quantify their interaction (see also Pruppacher and Klett, 1997; Flossmann et al., 2010—this issue).

In the 80s the first models were designed to put together the different pieces and obtain an overall picture of the importance of aerosol particle loading for the formation and evolution of the cloud. It became possible not only to study the role of the particles in the formation of a cloud, but also to study the cleaning capacity of the cloud in the overall pollution problem. A scientific review of the aerosol pollution impact on precipitation can be found in Levin and Cotton (2009). Also, the removal of accidental releases of particles by rain was an important issue (Cotton and Pielke, 1992).

Then, more recently, this interest was extended to climate issues, as the radiative properties of clouds change in relation with the particle spectrum that forms them (Twomey, 1974, 1977). New questions arose as to the interaction of pollution and climate change, and related issues of geo-engineering. Will an increase of the number of particles cause brighter clouds and, thus, counteract the global warming? Can seeding with hygroscopic particles force clouds to rain, fighting droughts in certain regions of the earth? What is the role of biological aerosol particles such as bacteria and virus in the propagation of diseases?

The questions about the cloud–aerosol interaction become more and more urgent and models try to give us some answers. However, the modelling of these processes is even more complicated than a meteorological precipitation modelling, due to severe grid scale problems. Aerosol particles have sizes between several nanometres and a few micrometers, and the size of a precipitation region extends over several hundred kilometres. The activation of aerosol particles to form drops or ice particles depends on the supersaturation, a variable not commonly predicted by synoptic scale models.

Since the 80s, our work is focussed on this question on an intermediate scale more finely resolved than synoptic scale models but more coarsely than process models.

The following review summarizes the main features of the models we have developed and the findings published from the numerous studies that were performed. This digested presentation will hopefully be useful to coarser scale models, and will highlight the role of supersaturation, allow identifying minor processes with respect to the important ones and support development of parameterizations for air quality, chemical transport and climate models.

2. Model description

2.1. The microphysics model

The microphysics model DESCAM (DEtailed SCAvenging Model) is under development since the 1980s and has been published in its different versions a number of times. Below the main features will be summarized, along with the main references for more details.

The information regarding the hydrometeor development is treated in a bin resolved way. Thus, the liquid water is