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Coupling aerosols to (cirrus) clouds in a global aerosol-climate model

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The impact of aerosol on atmospheric composition and climate still represents one of the largest uncertainties in the quantification of anthropogenic climate change. This is particularly the case for modelling aerosol-cloud interactions, which requires a detailed knowledge of various processes acting on a wide range of spatial and temporal scales. While significant progress has been made in developing parameterizations for describing the aerosol activation process in liquid clouds in the framework of global models, the aerosol-induced formation of ice crystals in cirrus clouds is still poorly understood and only a few global models include explicit representations of aerosol-cloud interactions in the ice phase. This is due to the high complexity of the freezing processes occurring in the ice phase, the uncertain properties of ice nucleating particles, and the competition between homogeneous and heterogeneous freezing at cirrus conditions. To tackle this issue, this study documents the implementation of a new cloud microphysical scheme, including a detailed parameterization for aerosol-driven ice formation in cirrus clouds, in the global chemistry climate model EMAC, coupled to the aerosol submodel MADE3. The new scheme is able to consistently simulate three regimes of stratiform clouds (liquid, mixed- and ice-phase/cirrus clouds), considering the activation of aerosol particles to form cloud droplets and the nucleation of ice crystals. In the cirrus regime, it allows for the competition between homogeneous and heterogeneous freezing for the available supersaturated water vapor, taking into account different types of ice-nucleating particles, whose specific ice-nucleating properties can be flexibly varied in the model setup. The new model configuration is tuned to find the optimal set of parameters that minimizes the model deviations with respect to observations. A detailed evaluation is performed comparing the model results for standard cloud and radiation variables with a comprehensive set of observations from satellite retrievals and in-situ measurements. The performance of EMAC-MADE3 in this new coupled configuration is in line with similar global coupled models and with other global aerosol models featuring ice cloud parameterizations. Some remaining discrepancies, namely a high positive bias in liquid water path in the northern hemisphere and overestimated (underestimated) cloud droplet number concentrations over the tropical oceans (in the extra-

tropical regions), which are both a common problem of this kind of models, need to be taken into account in future applications of the model. To further demonstrate the readiness of the new model system for application studies, an estimate of the anthropogenic aerosol effective radiative forcing (ERF) is provided, showing that EMAC-MADE3 simulates a relatively strong aerosol-induced cooling, but within the range reported in the IPCC AR5 and in other, more recent, assessments.