Radiative forcing of anthropogenic aerosols on cirrus clouds using a hybrid ice nucleation scheme

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Anthropogenic aerosols impact cirrus clouds through ice nucleation, thereby changing the Earth's radiation budget. However, the magnitude and sign of anthropogenic forcing on cirrus clouds are still very uncertain depending on the treatments for ice nucleating particles (INPs) and the ice nucleation scheme. In this study, a new ice nucleation scheme (hereafter the HYBRID scheme) is developed to combine the best features of two previous ice nucleation schemes, so that the global model is able to calculate the ice number concentration in both the updrafts and downdrafts associated with gravity waves and has a robust sensitivity to the change of aerosol number. The ice number concentrations calculated using the HYBRID scheme are overestimated somewhat but are in reasonable agreement with an adiabatic parcel model and observations. The forcing and cloud changes associated with changes in aircraft soot, sulfur emission and all anthropogenic emissions between the preindustrial period (PI) and the present day (PD) are examined using a global model with the HYBRID scheme. Aircraft soot emissions decrease the global average ice number concentration (Ni) by $-1.0\pm 2.4 \times 10^7$ m$^{-2}$ due to the inhibition of homogeneous nucleation and lead to a radiative forcing of $-0.14 \pm 0.07$ W m$^{-2}$, while the increase in the sulfur emissions increases the global average Ni by $7.3 \pm 2.9 \times 10^7$ m$^{-2}$ due to the increase in homogeneous nucleation and leads to a radiative forcing of $-0.02 \pm 0.06$ W m$^{-2}$. The possible effects of aerosol and cloud feedbacks to the meteorological state in remote regions partly contribute to reduce the forcing and the change in Ni due to anthropogenic emissions. The radiative forcing due to all increased anthropogenic emissions from PI to PD is estimated to be $-0.20 \pm 0.05$ W m$^{-2}$. If newly formed secondary organic aerosols (SOA) acts as INP and inhibit homogeneous nucleation, the Ni formed from heterogeneous nucleation is increased. As a result, the inclusion of INPs from SOA increases the change in Ni to $12.0 \pm 2.3 \times 10^7$ m$^{-2}$ and increases (makes less negative) the anthropogenic forcing on cirrus clouds to $-0.04 \pm 0.08$ W m$^{-2}$ from PI to PD.