Uncertainty in Estimation of Anthropogenic Aerosol Indirect Effect

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***Abstract*—In this paper, uncertainties in estimating anthropogenic aerosol indirect effects on warm clouds are explored using the recently developed Grid point Atmospheric Model (GAMIL) with prescribed aerosol fields. The anthropogenic aerosol indirect effect is calculated by the change in shortwave cloud forcing from preindustrial times to present-day. Simulations show anthropogenic aerosol indirect effect is not sensitive to two different physically-based droplet nucleation parameterizations. However, anthropogenic aerosol indirect effect is quite sensitive to the assumption on the sub-grid vertical velocities, which are used to drive physically-based droplet nucleation parameterization. Furthermore, sensitivity simulations indicate that aerosol influence on convective clouds, which is not considered in GAMIL model, might be an important contributor to anthropogenic aerosol indirect effect.**

Keywords-aerosol indirect effect; uncertainty; climate change

I. INTRODUCTION

Aerosol particles could modify the optical properties of warm clouds through the so-called aerosol indirect effect in which aerosol particles act as cloud condensation nuclei (CCN), thereby changing the cloud microphysical properties and hence radiative transfer [1,2]. Although the aerosol indirect effect has been studied extensively in the recent decades, it is still associated with a low level of understanding due to the complexity of the aerosol-cloud interaction, as well as the wide range of scale on which these interactions occur. In this paper, we investigate the uncertainty of anthropogenic aerosol indirect effect on warm clouds.

Linking aerosol particles to cloud droplet formation is the root of aerosol influence on warm clouds. In recent years, physically-based parameterizations have been widely used in global models. Here we firstly investigate the sensitivity of anthropogenic aerosol indirect effect to two different physically-based droplet nucleation parameterizations. Representation of clouds remains a big challenge in GCMs [3,4]. Some simplifications must be made due to the vast range of temporal and spatial scales in cloud processes [5]. The influences of these simplifications on aerosol indirect effect are also evaluated in this paper.

II. MODEL DESCRIPTION

The global atmospheric modeling tool in this study is the new version of Grid-point Atmospheric Model of IAP LASG (GAMIL). Compared to default GAMIL, the new developed GAMIL could represent aerosol indirect effect in a much more realistic manner [6]. In two-moment bulk stratiform cloud microphysics scheme scheme, droplet nucleation process is represented by the physically-based parameterization of Abdul-Razzak and Ghan (hereafter AG). Besides of this parameterization, another physically-based droplet nucleation parameterization developed by Nenes and Seinfeld (hereafter NS) has also been included [7, 8]. A sub-grid vertical velocity (W_{sub}) that incorporate the effect of sub-grid variability of vertical velocity on calculating droplet nucleation is provided. A lower limit of 0.1 m s^{-1} is assumed for weak turbulent diffusion. Prescribed aerosol data recommended by the Coupled Model Intercomparison Project (CMIP5) are used for droplet nucleation parameterization. The convective cloud processes are presented by the modified Zhang-McFarlane convective cloud scheme. The conversion of cloud water to rain is represented by a given coefficient C_0 (0.5×10^{-3} m^{-1} in GAMIL). The detrained cloud water is added to stratiform cloud. Number concentrations of convective detrainment are calculated by assuming a mean radiusof 16 μm and 32 μm for droplets (R_d) and ice crystals, respectively.

III. DIFFERENT PHYSICALLY-BASED DROPLET NUCLEATION PARAMETERIZATIONSU

All simulations in this paper were carried out in approximate $2.8^{\circ}\times2.8^{\circ}$ horizontal resolution and 26 vertical levels with a time step of 20 min, using climatological sea surface temperature. Each simulation was run for 5 years after an initial spin-up of 4 months. Anthropogenic aerosol indirect effects from two different physically-based droplet nucleation parameterizations (AG and NS, Table I) are examined here. Each experiment included two simulations, present-day (PD) simulation forced by annually-cyclic aerosol data for the 1990s and preindustrial (PI) simulation forced by aerosol data for the 1870s.

TABLE I. DESCRITPION OF ALL EXPERIMENTS IN THIS PAPER.

Experiments	Description
AG	AG, C_0=0.5*10^{-3} m^{-1},R_d=16μm, W_{sub}>0.1 m s^{-1}.
BN	same as AG, but using BN parameterization.
W_{sub}	same as AG, but W_{sub}>0.3 m s^{-1}.
C_0	same as AG, but C_0=3.0*10^{-3} m^{-1}.
R_d	same as AG, but R_d = 8μm, only for PI condition.

An overview of various global annual mean diagnostics is provided in Table II. Global mean column cloud droplet number concentrations with NS parameterization are larger than AG for both PD and PI conditions. This result is consistent with the tendency of NS parameterization to diagnose higher CCN than AG parameterization for most conditions [9]. Because of cloud lifetime effect, simulations with NS parameterization also produce larger liquid water path than AG simulations. Consequently, global annual mean short wave cloud forcing (SWCF) with NS parameterization are higher than AG parameterization, -1.4 W m^{-2} for PD condition and -1.5 W m^{-2} for PI condition. The anthropogenic aerosol indirect effect defined as the global mean difference in SWCF between PD and PI amounts -1.4 W m^{-2} with AG parameterization and -1.3 W m^{-2} with NS parameterization. The difference is remarkably small. This indicates that anthropogenic aerosol indirect effect is not sensitive to physically-based droplet nucleation parameterizations.

TABLE II. GLOBAL MEAN CLOUD PROPERTIES FROM VARIOUS SIMULATIONS FOR PD (SUFFIX PD) AND PI CONDITION (POSTFIX PI).

Experiments	SWCF(W m^{-2})	LWP (g m^{-2})	CDNUMC(10^{10} m^{-2})
AG_{PD}	-53.9	61.6	1.70
AG_{PD}	-52.5	59.0	1.49
NS_{PD}	-55.3	63.4	1.76
NS_{PI}	-54.0	60.4	1.55
W_{subPD}	-56.4	69.1	2.18
W_{subPI}	-54.2	62.4	1.66
C_{0PD}	-50.0	54.4	1.58
C_{0PD}	-48.3	51.4	1.33
R_{dPI}	-54.6	74.7	2.10

IV. UNCERTAINTIES IN CLOUD SCHEME

Global models with their grid spacing of the order of 100 km are unable to resolve cloud scale vertical motions. Thus, global models provide only one characteristic updraft velocity that denotes the influence of sub-grid variability of vertical velocity on droplet nucleation. In this method, a minimum of updraft velocity is usually assumed, and this minimum value is treated as a tuning parameter because it is difficulty to constrain the sub-grid variability with current observations [10]. In GAMIL, the minimum value is set to 0.1m s^{-1} following [5]. It is lower than other study (0.3 m s^{-1} in [11]). In order to evaluate the impact of this lower limit on aerosol indirect effect, we set up a sensitivity experiment (W_{sub}, Table I), in which the minimum value was increased to 0.3 m s^{-1}. Because activated aerosol number fraction strongly depends on updraft velocity, global mean column cloud droplet number concentrations from W_{sub} experiment are remarkably larger than AG experiment, especially for PD condition (Table II). As a result, anthropogenic aerosol indirect effect from W_{sub} is increased to -2.2 W m^{-2}, which is remarkable larger than AG (-1.4 W m^{-2}).

The aerosol influence on convective clouds is not included in the current estimations of aerosol indirect effect because it is very difficulty for GCMs to explicitly parameterize this indirect effect [9]. In Zhang-McFarlane convective cloud scheme, the conversion of suspended liquid water droplets to rain is described by a tunable parameter C_0 (2.0×10^{-3} m^{-1}, [12]). Actually, C_0 denotes several individually microphysical processes that strongly depend on droplet number concentration. So that C_0 should be relevant to aerosols. Besides, the droplets radius of convective detrainment (R_d), which is a tunable parameter, should also be relevant to aerosols. Here, we try to figure out if the impact of aerosols on convective clouds is an important component for simulating aerosol indirect effect. To do so, two sensitivity experiments (Table I) are constructed by changing these above two tunable parameters, C_0 and R_d. Because C_0 was raised to 3.0×10^{-3} m^{-1}, global mean liquid water path from C_0 simulation is significantly decreased, by 7.2 g m^{-2} compared to AG simulation for PD condition (Table II). The anthropogenic aerosol indirect effect from C_0 experiment (-1.7 W m^{-2}) is remarkably larger than AG (1.4 W m^{-2}). Because R_d was reduced from 16μm to 8μm, column droplet number from R_d simulation is significantly increased, by 0.61×10^{10} m^{-2} as compared to AD under PI condition. Furthermore, global mean shortwave cloud forcing from R_d simulation is increased by -2.1 W m^{-2} (Table II). This difference is remarkably larger than anthropogenic aerosol indirect effect using AG parameterization (1.4 W m^{-2}). Roughly speaking, aerosol effects on convective clouds might be an important component for quantifying aerosol indirect effect.

V. CONCLUSION AND DISCUSSION

The root of aerosol indirect effect is the droplet nucleation process. Several years ago, in most GCMs, droplet nucleation process was parameterized by empirical correlations between aerosols and droplets number concentrations. Previous studies showed that different empirical correlations could lead to a wide range of anthropogenic changes in the net radiative flux at the top of the atmosphere. In recent years, physically-based droplet nucleation parameterizations have been widely used in GCMs [9]. It seems that anthropogenic aerosol indirect effect is not sensitive to two different physically-based droplet nucleation parameterizations. However, anthropogenic aerosol indirect effect is quite sensitive to the sub-grid vertical velocities, which are used to drive droplet nucleation parameterization.

Simulations in this paper show that annual global mean shortwave cloud forcing is sensitive to many tunable parameters in deep convective cloud scheme which should be relevant to aerosols. This indicates that aerosol impact on convective clouds might be an important component for quantifying aerosol indirect effect. Although it is very difficulty for GCMs to explicitly parameterize aerosol effects on convective clouds, recent developments show that this some GCMs start to address this issue [13, 14].

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