7.4 SIMULATION OF AEROSOL EFFECTS ON CLIMATE SYSTEM BY AEROSOL CLIMATE MODEL

Toshihiko Takemura*
Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan

1. INTRODUCTION

A change in the aerosol loading in the atmosphere is assumed to cause climate change through the direct and indirect effects. The direct effect is that aerosol particles scatter and absorb the solar and thermal radiation. The indirect effect is that an increase in the aerosols loading causes a decrease in the cloud droplet size acting as cloud condensation nuclei, leading to and increase in the cloud albedo (1st indirect effect) and an increase in the cloud lifetime and consequently suppression of precipitation (2nd indirect effect). The semi-direct effect is also discussed, which the atmosphere is stabilized by radiative absorption of aerosol particles and consequently cloud is suppressed. A lot of past studies estimated the aerosol radiative forcing, which is an index of climate change and one of the principal roles in the Intergovernmental Panel on Climate Change (IPCC). However, there are few studies on specific analysis on climate change due to the aerosol effects. Modeling studies are available to analyze it including the intricate feedback mechanism. In this study, the climate change by aerosol particles is considered with a global aerosol climate model, SPRINTARS (Spectral Radiation-Transport Model for Aerosol Species). Changes in the cloud water and precipitation with and without the feedback mechanism related to the aerosol effects are discussed. Also time series of the radiative forcing at the surface as well as at the tropopause are calculated and the relationship with the surface air temperature is discussed.

2. MODEL DESCRIPTION

In this study effects of anthropogenic aerosols on the climate system are analyzed from simulations by a general circulation model, MIROC, coupled with an on-line aerosol transport-radiation model, SPRINTARS. The MIROC is a coupled atmosphere-ocean general circulation model developed by Center for Climate System Research, University of Tokyo (CCSR), National Institute for Environmental Studies (NIES), and Frontier Research Center for Global Change (FRCGC) (K-1 Model Developers 2004). The SPRINTARS is one of the components in the MIROC to simulate aerosol distributions and interaction with the climate system. It treats the aerosol direct, semi-direct, and indirect effects due to main tropospheric aerosols, i.e., black carbon (BC), organic carbon (OC), sulfate, soil dust, and sea salt. The aerosol transport processes include emission, advection, diffusion, sulfur chemistry, wet deposition, dry deposition, and gravitational settling. The emission of natural aerosols, such as soil dust, sea salt, and DMS that is a precursor gas of sulfate, are calculated on-line with some parameters (wind velocity, vegetation, etc.). Historical data of anthropogenic emissions for BC, OC, and SO_2 are edited by the NIES research group based on several emission and statistical database. The cloud droplet number concentration for water is diagnosed from a parameterization with number concentrations, size distributions, and chemical properties of aerosol particles, updraft velocity, and curvature effect. The cloud droplet effective radius and precipitation rate are then calculated from the diagnosed cloud droplet number concentration. The radiation scheme in MIROC is extended for scattering and absorption by aerosol particles depending on the refractive index, size distribution, and hygroscopic growth, and for a change in the cloud albedo depending on the aerosol particle number concentration. Aerosol concentrations and optical parameters simulated by SPRINATRS are in reasonable agreement with ground-based, aircraft, and satellite observations (Takemura et al. 2000, 2002, 2003). The detailed description for SPRINTARS is in Takemura et al. (2005). Daily and monthly mean data related to aerosols from the year 1996 to the present simulated by SPRINTARS are uploaded to http://cfors.riam.kyushu-u.ac.jp/~toshi/SPRINTARS/catalogue/.

3. RESULTS AND DISCUSSION

Here three different scenarios of aerosol emissions and greenhouse gas (GHG) concentrations are simulated with the mixed-layer

* *Corresponding author address:* Toshihiko Takemura, Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan; e-mail: toshi@riam.kyushu-u.ac.jp.

ocean in order to analyze the aerosol effects on climate: present aerosols and present GHGs experiment (E1), pre-industrial aerosols and present GHGs experiment (E2), and pre-industrial aerosols and pre-industrial GHGs experiment (E3). The difference between E1 and E2 (E1-E2) is due to a change in aerosols only, while E1-E3 is due to a change both in aerosols and GHGs. Each equilibrium experiment is integrated for fifty years and analyzed for the last thirty years. It consists of three ensemble simulations starting from different initial conditions to reduce uncertainties of simulations. Experiments E1 and E2 are repeated as E1f and E2f respectively, for nudged wind, atmospheric temperature, and specific humidity by 6-hourly NCEP/NCAR reanalysis data as well as prescribed sea surface temperature and sea ice to exclude any feedbacks due to the aerosol effects.

The increase in the cloud water path over most regions simulated by the prescribed meteorological field without the mixed-layer ocean indicates the aerosol second indirect effect that is the cloud microphysical response to the added anthropogenic CCN especially in aerosol-loaded areas of Asia, eastern US, northern and tropical Atlantic, and Europe (Fig. 1a). On the other hand, the cloud water decreases mainly due to reducing solar insolation, temperature, and evaporation at the surface in the simulation relaxing the restriction on the meteorological field with the mixed-layer ocean, except for East Asia and North America where anthropogenic aerosols are heavily loaded (Fig. 1b). A change in the hydrological cycle due to dimming by aerosols also affects a variability of the cloud water in the tropics. With the effects both of aerosols and GHGs, the cloud water still decreases in South Asia because absorbing and hydrophobic aerosols such as black carbon may reduce hydrological cycle through the feedback mechanism, though global warming increases the cloud water in most areas (Fig. 1c). The cloud water also decreases in the sub-tropics.

Anthropogenic aerosols suppress the precipitation over land through the aerosol second indirect effect in the experiment with the prescribed meteorological field, though there are no systematic changes in the remote ocean (Fig. 2a). Relaxing the restriction on the meteorological field allow a decrease (increase) in the precipitation according to a decrease (increase) in the cloud water (Figs. 1b and 2b). However, in the East Asia, the simulation even including the feedback mechanism indicates an increase in the cloud water path and a simultaneous decrease in the precipitation, which suggests that the second indirect effect is severe. The simulated

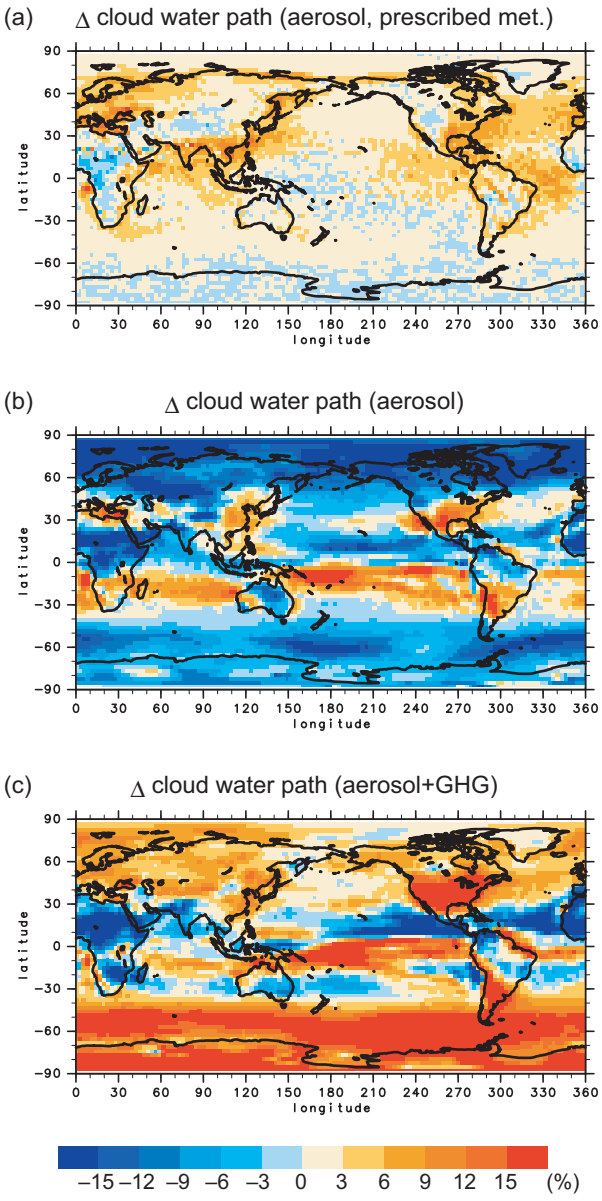

FIG. 1. Annual mean distributions of changes in the simulate cloud water path from the pre-industrial era to the present with changes in (a) aerosols with prescribed meteorological field (difference between the experiments E1f and E2f, (b) aerosols without restrictions on the meteorological fields including feedback (difference between E1 and E2), and (c) both aerosols and GHGs without restrictions on the meteorological fields including feedback (difference between E1 and E3).

precipitation both with anthropogenic aerosols and GHGs can be compared with historical observational data (Fig. 2c). The observed trend of

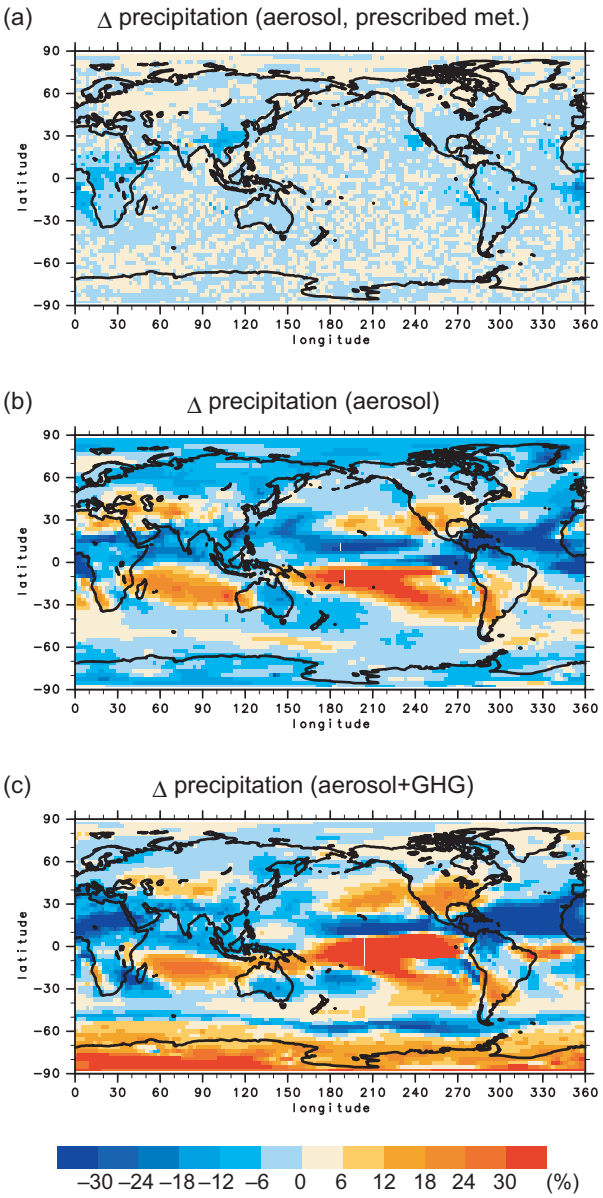

FIG. 2. Annual mean distributions of changes in the simulate precipitation from the pre-industrial era to the present with changes in (a) aerosols with prescribed meteorological field (difference between the experiments E1f and E2f, (b) aerosols without restrictions on the meteorological fields including feedback (difference between E1 and E2), and (c) both aerosols and GHGs without restrictions on the meteorological fields including feedback (difference between E1 and E3).

a change in the annual precipitation in the 20th century reveals a decrease of several tens percents in the Sahel and central Africa and an increase in most areas of the North America (IPCC 2001). These tendencies are simulated well in the model, and a comparison between Figs. 2b and 2c indicates that the aerosol effect with the feedback mechanism contributes to these precipitation changes from pre-industrial era to the present. The simulation suggests that anthropogenic aerosols accelerate drought in the Sahel through the feedback mechanism.

This study also shows time series of the instantaneous radiative forcings for main forcing agents from the year 1850 to 2000 at the the surface as well as at the tropopause. This evaluation corresponds to a simulation of 20th century climate with a synthetic coupled atmosphere-ocean general circulation model (Nozawa et al. 2005). Figure 3a shows that the radiative forcing of GHGs is calculated to be +2.1 W m^{-2} at the tropopause in 2000, which is the lower limit of the uncertainty in the IPCC estimation (IPCC 2001). The radiative forcings of an increase in tropospheric O_3 and a decrease in stratospheric O_3 are estimated to be +0.4 and –0.2 W m^{-2}, respectively at the tropopause, which are within a range of the IPCC estimation (IPCC 2001). Negative forcings of sulfate and OC and a positive forcing of BC by the direct effect nearly cancel the global mean radiative forcing each other, consequently the total forcing due to the aerosol direct effect at the tropopause is small negative forcing of –0.1 W m^{-2} in 2000. The each aerosol direct radiative forcing for sulfate, OC, and BC is estimated to be –0.2, –0.3, and +0.4 W m^{-2}, respectively (Takemura et al. 2005). The radiative forcings of the first and second aerosol indirect effects in 2000 are estimated to be –0.6 and –0.4 W m^{-2}, respectively.

On the other hand, as shown in Figure 3b, the positive radiative forcing of GHGs at the surface (+0.4 W m^{-2} in 2000) is much smaller than that at the tropopause. The positive forcing of tropospheric O_3 and negative forcings of the aerosol indirect effect and at the surface also decrease in comparison with those at the tropopause. However, the negative forcing of the aerosol direct effect at the surface is much larger, which is estimated to be –1.6 W m^{-2} in 2000. There is little difference in the direct radiative forcing between the tropopause and the surface for OC and sulfate aerosols that principally scatter the incident solar radiation back to the space, whereas BC strongly absorbs the radiation in the troposphere and attenuates the solar radiation reaching the surface (Takemura et al. 2005). Consequently the negative total radiative forcing at the surface rapidly increases between 1955 and 1965.

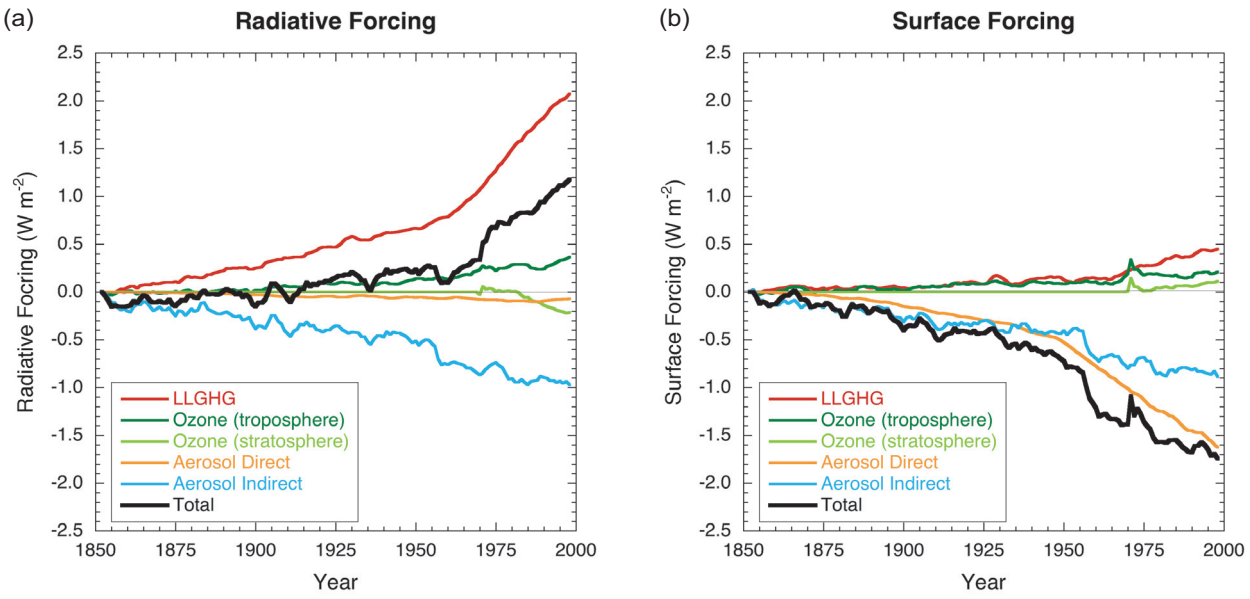

FIG. 3. Time evolution of global mean instantaneous radiative forcings from 1850 to 2000 under all-sky condition due to various climate forcing agents at the (a) tropopause and (b) surface in W m^{-2}. They are 5-years running means for annual averages.

The rapid increase in the radiative forcing at the tropopause mainly due to GHGs has a good correlation with global warming after 1970, while the sharp decrease in the radiative forcing at the surface principally due to aerosols is correspondent to the cooling atmosphere in the mid-20th century. This study suggests that a simultaneous analysis of changing rates of the radiative forcing both at the tropopause and surface can explain tendencies of decadal-scale changes in the surface air temperature.

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REFERENCES

IPCC, 2001: *Climate Change 2001: The Scientific Basis*. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., Cambridge Univ. Press, Cambridge, UK.

K-1 Model Developers, 2004: *K-1 coupled GCM (MIROC) description*. K-1 Tech. Rep. 1, H. Hasumi, and S. Emori, Eds., Univ. of Tokyo, Tokyo.

Nozawa, T., T. Nagashima, H. Shiogama, and S. A. Crooks, 2005: Detecting natural influence on surface air temperature change in the early twentieth century. *Geophys. Res. Lett.*, **32**, L20719, doi:10.1029/2005GL023540.

Takemura, T., H. Okamoto, Y. Maruyama, A. Numaguti, A. Higurashi, and T. Nakajima, 2000: Global three-dimensional simulation of aerosol optical thickness distribution of various origins. *J. Geophys. Res.*, **105**, 17853–17873.

Takemura, T., T. Nakajima, O. Dubovik, B. N. Holben, and S. Kinne, 2002: Single-scattering albedo and radiative forcing of various aerosol species with a global three-dimensional model. *J. Climate*, **15**, 333–352.

Takemura, T., T. Nakajima, A. Higurashi, S. Ohta, and N. Sugimoto, 2003: Aerosol distributions and radiative forcing over the Asian-Pacific region simulated by Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS). *J. Geophys. Res.*, **108**(D23), 8659, doi:10.1029/2002JD003210.

Takemura, T., T. Nozawa, S. Emori, T. Y. Nakajima, and T. Nakajima, 2005: Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. *J. Geophys. Res.*, **110**, D02202, doi:10.1029/2004JD005029.