Potentiality of Aerosols in Changing the Precipitation Field in Asia

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Abstract

We performed an experiment under ideal conditions using a general circulation model and found that aerosols can play an important role in altering the precipitation in Asia. Emissions of anthropogenic aerosols are increasing in Asia, affecting the global and regional climates through their direct and indirect effects. However, the link between aerosol loading and climate change due to these effects is still difficult to understand. The present study was based on a three-dimensional aerosol transport model coupled with a mixed-layer ocean model; it focused on the effects of anthropogenic aerosols on boreal summer precipitation over Asia. We investigated these effects by taking differences between the results of equilibrium runs with pre-industrial and current fossil fuel burning aerosol (FFA) conditions. In this model simulation, aerosol loading changed the circulation field through changes in the radiation budget. The indirect effects of aerosols include not only the first and second indirect effects but also the effects of these changes. Our results show that an increase in anthropogenic aerosols reduces precipitation due to weaker convection with both surface cooling and sea surface temperature (SST) changes. This mechanism is the most effective way for aerosols to impact precipitation in this model simulation.

1. Introduction

Aerosols have been recognized as an important modulator of the earth's climate through various mechanisms. In addition to temperature change due to aerosol direct and indirect forcing, recent studies have suggested that aerosols have a significant potential to change precipitation (Menon et al. 2002; Ramanathan et al. 2005; Lau et al. 2006; Zhang et al. 2007). The analysis of Mukai et al. (2008) shows that an increase in anthropogenic aerosols reduces solar radiation over Asia. In the present study, we investigated the role of aerosols in producing complex changes in boreal summer precipitation. The rainfall is higher in summer, and the aerosol effects are more evident in the precipitation in summer than in any other season in the simulations.

2. Methods

The three-dimensional aerosol transport model, SPRINTARS driven by the CCSR/NIES/FRCGC atmosphere general circulation model (AGCM) (K-1 Model Developers 2004) was used in the present study. The horizontal and vertical resolutions of triangular truncation were set at T42 (approximately 2.8 by 2.8 in latitude and longitude) and 20 layers, respectively. This model considered carbonaceous, sulfate, mineral dust and sea salt aerosols. The first and second indirect effects were taken into account using a parameterisation (Takemura et al. 2005). We monitored SST changes using a simplified mixed-layer ocean under the prescribed surface heat flux, which was previously calculated using a given SST.

To avoid uncertainties in the time evolution of aerosol loading and for simplicity, we took the differences between the results of equilibrium runs with current and pre-industrial aerosol conditions. Initially, we used the current FFA emission data provided by CCSR/NIES/FRCGC (experiment 1-1). In another experiment, we used pre-industrial era emission data that assumed no FFA emissions (experiment 1-2). Both experiments ran with current greenhouse gas (GHG) conditions. The FFA impact was evaluated from the differences between the results of the experiments 1-2 and 1-1. To compare the effects of FFA with those of GHG, we performed another series of equilibrium experiment runs with pre-industrial FFA and GHG conditions (experiment 1-3). GHG effects were calculated from the differences between the experiments 1-2 and 1-3. Likewise, the differences between the experiments 1-1 and 1-3 yielded the effects of both FFA and GHG. Each experiment was integrated for 50 years, and the averaged data over the last 30 years were used for investigation. In addition, we simulated two more experiments without a simplified mixed-layer ocean with the following settings: one with climatological SST (experiment 2-1) and another superposing the SST changes estimated by the experiments 1-1 and 1-2 on the climatological SST (experiment 2-2). Both experiments ran for 3 years using the current GHG and FFA, and the averaged data over the last 2 years were available for further analysis. The effects of SST change caused by FFA increase were estimated from the differences between these two experiments.

3. Aerosol effects on the precipitation

The difference between the experiments 1-1 and 1-2 yields an increase in aerosol loading. Figure 1 illustrates

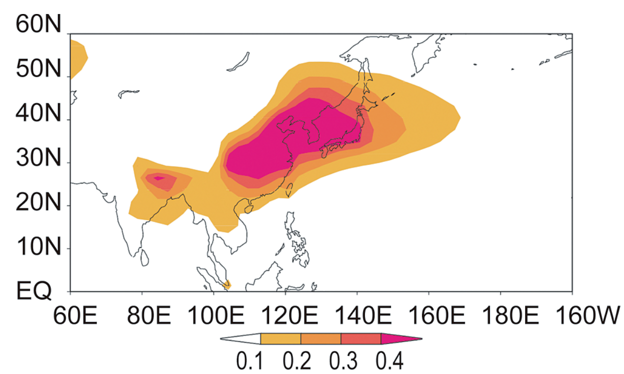

Fig. 1. Change in aerosol optical thickness due to FFA calculated by SPRINTARS in summer (JJA).

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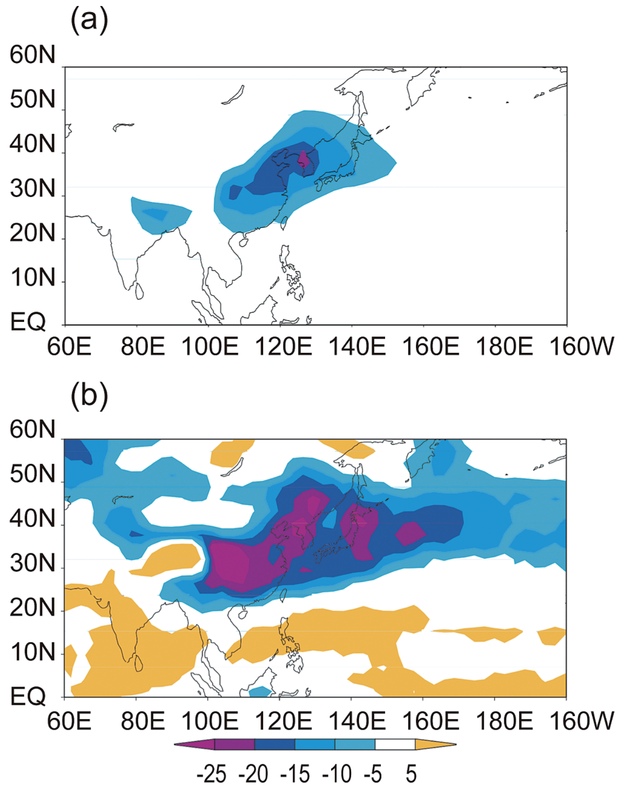

Fig. 2. Same as Fig. 1 but for (a) downward shortwave radiation flux (clear sky) and (b) downward shortwave radiation flux (whole sky) [W m^{-2}].

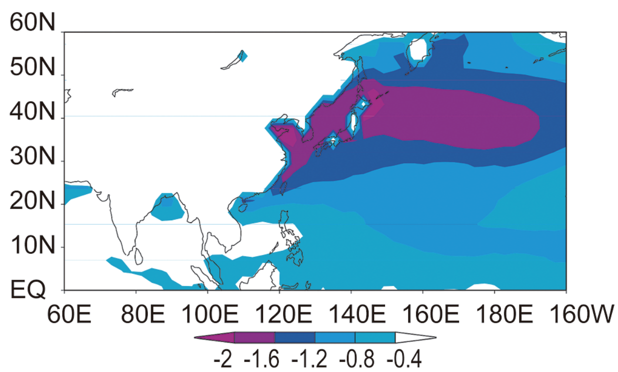

Fig. 3. Same as Fig. 1 but for SST [K].

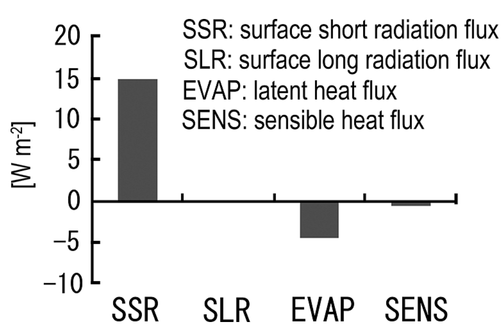

Fig. 4. Changes in surface radiation flux for FFA calculated by SPRINTARS in summer (JJA) average over 30 °N–50°N and 120°E–180°E. Upward directions indicate positive.

the distribution of the aerosol optical thickness at a wavelength of 550 nm calculated by SPRINTARS for summer (June, July and August; JJA). Large FFA loading is clearly seen in the middle latitude zone (30 °N to 60°N), in particular in the East Asia region. The increase of FFA effects on the surface radiation budget was caused by direct scattering and absorbtion of solar radiation and by indirect changes in the optical properties of clouds.

Figure 2 shows the aerosol effects on the surface downward shortwave radiation flux for both clear and whole sky conditions, which are defined as aerosol direct (Fig. 2a) and aerosol direct plus indirect effects (Fig. 2b), respectively. Therefore, the difference between Figs. 2a and 2b is presumed to be the aerosol indirect effect. The aerosol direct effect has similar distribution independent of the increase in aerosol optical thickness. A large decrease in the surface downward shortwave radiation flux is visible near the FFA source area, while the aerosol indirect effect spreads over a wider area, as shown in Fig. 2b. Thus, an increase in FFA reduced downward shortwave radiation flux around large aerosol loadings but in much wider regions than those of significant aerosol emission. In this model simulation, aerosol loading modified the circulation field through changes in the radiation budget. Accordingly, the aerosol indirect effects include not only the first and second indirect effects but also the effects of these changes.

The decrease in radiation flux reaching the surface can also change the SST. For instance, Fig. 3 illustrates the change in SST with the FFA increase. The simulated results show that SST changes are mostly negative and distributed over the middle latitude zone where surface downward shortwave radiation flux is reduced by aerosol effects. The change in radiation budget at the surface averaged over 30°N to 50°N and 120°E to 180°E is shown in Fig. 4. On average, the FFA optical thickness increases by 0.2 and SST decreases by 1.4 degrees over this region. This feature indicates that the change in surface shortwave radiation flux caused by the FFA increase represents the strongest influence upon the SST decrease in this case. Consequently, SST changes are expected to modify significantly the precipitation levels in this region.

Changes in vertical flow are shown in Fig. 5. The updraft flow becomes weaker over northeast China and Japan and stronger in the south of Japanese islands; it becomes weaker again in the subtropical region. The decrease in updraft flow in the subtropical area, together with the weakened southwesterly winds blowing from the west coast of India, suggests attenuation of

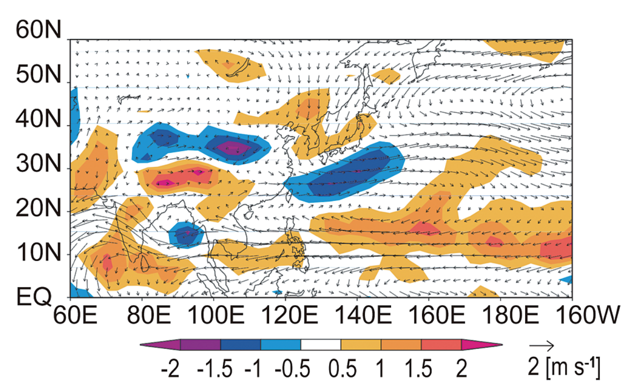

Fig. 5. Same as Fig. 1 but for pressure velocity at 400 hPa [10^{-2} Pa/s] (shaded) and wind velocity at 850 hPa [m s^{-1}] (vectors).

the summer monsoon circulation. Figure 6 illustrates the simulated precipitation changes because of the FFA impact. The model results show complicated spatial distributions of precipitation, which can be easily understood based on the fact that precipitation is caused by divergence/convergence processes of moist air masses (see also Fig. 5).

To investigate the relationship between SST changes induced by the FFA increase and precipitation changes, we performed experiment 2. Chung and Ramanathan (2006, 2007) reported that the SST gradient is the most sensitive parameter by which aerosols affect precipitation. The amount of SST changes obtained from experiments 1-1 and 1-2 was used as a representative case of SST variation caused by FFA. The quantitative difference in simulated precipitation for experiments 2-1 and 2-2 is shown in Fig. 7. These results indicate that summer precipitation decreases in a particular area around 20°N. The pattern of precipitation change due to FFA impact is similar near this area, as shown in Fig. 6. Detailed analyses of circulation patterns in the same area indicate that the summer precipitation decrease induced by FFA is caused by weakened Hadley circulation and summer Asian monsoon circulation due to SST cooling in the middle latitudes (Mukai et al. 2008). The precipitation changes from the Korean Peninsula to Japan visible in Fig. 6 are not apparent in Fig. 7. This suggests that surface land cooling is an important factor for precipitation changes in this area, because only a decrease in SST was considered in experiment 2. (i.e., a decrease in land surface temperature was not taken into account). This experiment suggests that a remarkable decrease in summer precipitation over the ocean is governed by the SST changes associated with the FFA increase. Therefore, our results show that an increase in anthropogenic aerosols reduces precipitation because of weaker convection associated with both land surface temperature and SST changes.

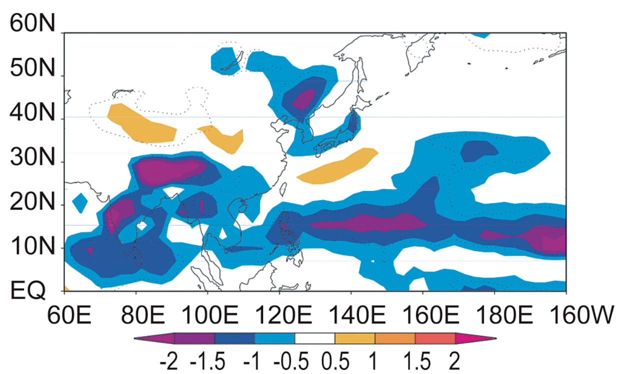

Fig. 6. Same as Fig. 1 but for precipitation [mm day^{-1}]. The dashed black curve indicates areas with significant simulated change of precipitation > 95%. The two-sample t-test is used.

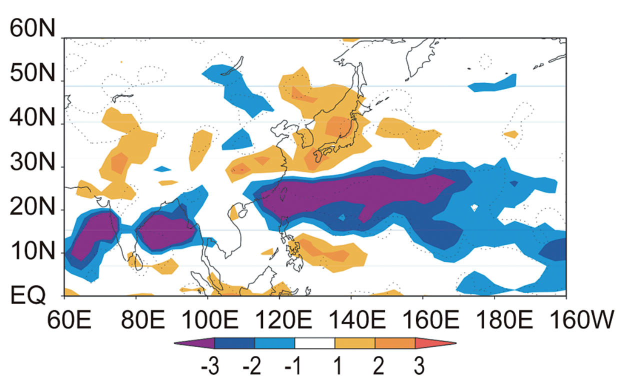

Fig. 7. Change in JJA precipitation for experiment 2 [mm day^{-1}]. The dashed black curve indicates areas with significant simulated change of precipitation > 95%. The two-sample t-test is used.

4. Comparison with observed trends

We also included the effect of GHG to compare it with that of FFA. Precipitation changes caused by FFA and/or GHG were estimated from the three experiments described in Section 2. The changes in precipitation caused by both FFA and GHG are shown in Fig. 8. The effects of GHG on the climate are different from those driven by FFA. For example, surface warming and cooling can occur due to GHG and FFA, respectively. The decrease in precipitation shown in northern China and northern India is similar to the change due to FFA alone (see Fig. 6). In addition, the patterns of precipitation change over the Bay of Bengal and the South China Sea associated with FFA and GHG effects (visible in Fig. 8) are different when only FFA effects are taken into account. These model results should be compared with observed regional trends of precipitation.

The comparison of model results with observed precipitation data is problematic, because the simulated changes were obtained from differences between only two experiments, while the observed changes follow secular trends. Apart from that, this comparison is feasible in our study. Thus, we selected five regions with characteristic precipitation changes in both observed data and simulation results. We compared the simulated results of precipitation change with observations over the long term (see Fig. 9). We used the precipitation data of Xie et al. (2007) in this comparison. The large precipitation increase in the Yangtze River basin (China_E) and a decreasing trend in northern China (China_N) have been reported by past studies (Endo et al. 2005; Xu et al. 2006). Our simulations indicate that the FFA impact mostly causes a strong decrease in precipitation in China_N, whereas it decreases precipitation in China_S and China_E. In contrast, the GHG impact

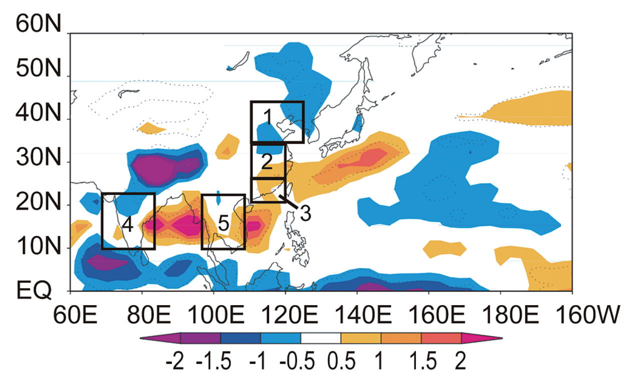

Fig. 8. Change in precipitation for FFA & GHG calculated by SPRINTARS in summer (JJA) [mm day^{-1}] in five regions, 1: China_N (35-45°N, 110-125°E), 2: China_E (25-35°N, 110-120°E), 3: China_S (20-25°N, 110-120°E), 4: Central India (10-23°N, 70-85°E), 5: Central Indo-China (10-23°N, 95-108°E). The dashed black curve indicates areas with significant simulated change of precipitation > 95%. The two-sample t-test is used.

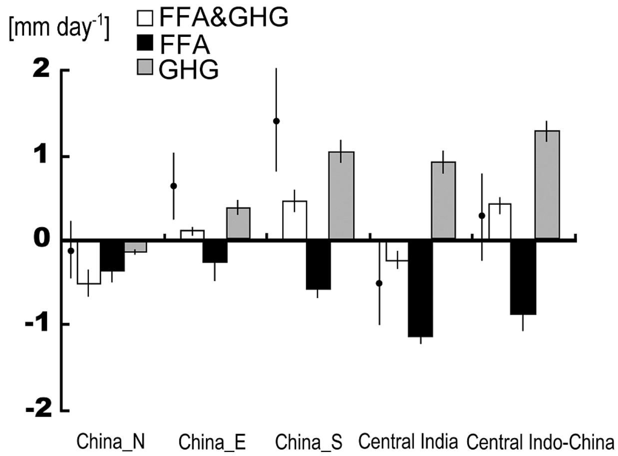

Fig. 9. Changes in summer precipitation in the five regions shown in Fig. 8. Bar graphs represent the results for FFA, GHG and FFA & GHG calculated by SPRINTARS [mm day^{-1}]. The filled circles denote observed precipitation trends from 1978 to 2002 [mm/day/10yr]. The line bars indicate standard deviations.

increases precipitation in those two Chinese regions. The total effects of GHG and aerosols were qualitatively consistent with the observed precipitation trends without one of both impacts. Using GCM simulations, Cheng et al. (2005) pointed out that the flooding trend in eastern China is more likely caused by strengthened convective precipitation associated with increases in SST and GHG. Our simulations suggest that the increased precipitation in the Yangtze River basin evokes a response of large-scale surface temperature change including SST change. Menon et al. (2002) have shown that black carbon aerosols cause a significant change in the precipitation field in Asia. They attributed this phenomenon to the increasing trend of precipitation in southern China associated with the thermal stratification change due to heating of the atmosphere by soot particles. We found a similar result with fixed SST, thus confirming this conclusion. However, when letting SST change in the simulation, the precipitation changes could be caused by aerosols even if changes in black carbon are not included. Conversely, according to our simulations, the central India and central Indo-China regions should show precipitation changes as a result of the competing effects of GHG and FFA. Observational data seem to support this conclusion. When comparing the effects of GHG and those of FFA, we found that both are comparable in these regions. Nevertheless, inconsistencies between model simulations and observed trends still remain; thus a more detailed analysis is warranted.

5. Conclusions

The effects of FFA on precipitation were investigated using model simulations. An increase in FFA alters the circulation field through changes in the radiation budget and reduces precipitation through convection weakening, which in turn is connected to surface cooling and SST changes. Comparison of model results with observed trends indicates it is difficult to reproduce observational precipitation data based solely on anthropogenic aerosol effects. However, the increase in anthropogenic aerosols is potentially significant in changing the precipitation levels over several regions in Asia.

Acknowledgments

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