Dependence of Precipitation Scaling Patterns on Emission Scenarios for Representative Concentration Pathways

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ABSTRACT

Pattern scaling is an efficient way to generate projections of regional climate change for various emission scenarios. This approach assumes that the spatial pattern of changes per degree of global warming (scaling pattern) is the same among emission scenarios. The hypothesis was tested for the scaling pattern of precipitation by focusing on the scenario dependence of aerosol scaling patterns. The scenario dependence of aerosol scaling patterns induced the scenario dependence of the surface shortwave radiation scaling pattern. The scenario dependence of the surface shortwave radiation scaling pattern over the ocean tended to induce the scenario dependence of evaporation scaling patterns. The scenario dependence of evaporation scaling patterns led to the scenario dependence of precipitation scaling patterns locally and downwind. Contrariwise, when the scenario dependence of aerosol scaling patterns occurred over land, the scenario dependence of surface shortwave radiation scaling patterns induced the scenario dependence of the scaling patterns of evaporation, surface longwave radiation, and sensible heat. Consequently, the scenario dependence of evaporation scaling patterns tended to be insignificant. Moreover, the scenario dependence of the southern annular mode and polar amplification caused some of the scenario dependence of precipitation scaling patterns. In this study, only one global climate mode was analyzed. In addition, sensitivity experiments that remove aerosol emissions from some regions or some kinds of aerosols are ideal to separate the impacts of aerosols. Thus, an analysis of the dependencies of precipitation scaling pattern among global climate models and the sensitivity experiments are required in future work.

1. Introduction

Global-mean surface air temperature (SAT) is projected to increase throughout the twenty-first century as a result of anthropogenic CO₂ emissions. Precipitation is one of the most important climate variables in studies of the impact of global warming and adaptation to climate change. Global-mean precipitation is projected to increase because of the increase in the amount of tropospheric water vapor associated with a warmer climate. The rate of change of a variable \( X \), such as precipitation, with respect to SAT is here defined to be the temperature coefficient of \( X \), while the relative change of \( X \) per degree of global warming is defined as the sensitivity of \( X \) to SAT. Although the temperature coefficient of global-mean precipitation is positive, the sensitivity of precipitation to SAT is small compared with the corresponding sensitivity of water vapor estimated by the Clausius–Clapeyron relationship. The reason is that the overall intensity of the hydrologic cycle is controlled not by the availability of moisture but by the availability of energy:
in particular, the extent to which the troposphere can radiate away latent heat released by the condensation of water vapor (Allen and Ingram 2002).

Both aerosols (Shiogama et al. 2010a; Shindell et al. 2012) and greenhouse gases induce changes in the amount of precipitation. Aerosol particles absorb and/or scatter incoming solar radiation and thereby reduce the downward flux of shortwave radiation at the surface (Ramanathan et al. 2001; Ramanathan and Carmichael 2008). In addition to this so-called direct effect, aerosols also influence the microphysical properties of clouds by acting as cloud condensation nuclei. Modifications to the microphysical properties of clouds lead to the enhancement of their albedo and lifetime (first-order and second-order indirect effects, respectively). These first-order and second-order indirect effects consequently lead to reductions in the flux of solar radiation to the ground (Lohmann and Feichter 2005), and these reductions result in a decrease of local evaporation because of the decrease in the energy available for evaporation from the surface. Finally, the decrease of evaporation causes a decrease in local precipitation. Previous research has in fact shown that aerosol particles reduce precipitation over China (Qian et al. 2009), India (Ramanathan et al. 2001; Meehl et al. 2008; Wang et al. 2009), and western Africa (Kawase et al. 2011).

Research related to the impacts of global warming and adaptations to climate change require the use of climate models based on many different concentration pathways. Atmosphere–ocean general circulation models (AOGCMs) are the most promising for simulating future climates (Mitchell et al. 1999). However, the use of an AOGCM to simulate future climates for many different socioeconomic scenarios requires very large computer resources. A simpler and more efficient method is therefore necessary to generate these projections.

Pattern scaling is a very useful method for generating climate simulations (Mitchell et al. 1999; Schlesinger et al. 2000). The determination of the applicability of pattern scaling, however, requires further investigation by the climate modeling community, and the results of such studies should be communicated rapidly to scientists studying the impacts of climate change and adaptations thereto (Moss et al. 2007). In pattern scaling, the spatial pattern of the temperature coefficient of a climate variable (scaling pattern) is estimated by using simulations performed with a general circulation model (GCM) subject to a certain emission scenario. Simple climate models (e.g., Meinshausen et al. 2011) that include energy balance equations and a simple carbon cycle on a global scale are then used to estimate global-mean SAT changes for a very wide range of emission scenarios. Finally, regional climatic changes for these emission scenarios are estimated by multiplying the global-mean SAT changes by the scaling pattern.

The basic assumption of pattern scaling is that the scaling patterns are the same for all emission scenarios (Shiogama et al. 2010b). Previous research, however, has pointed out that there is a robust scenario dependence of temperature scaling patterns because of nonlinear relationships in the climate system and differences among emission scenarios in the scaling patterns of anthropogenic aerosols (Mitchell et al. 1999; Schlesinger et al. 2000; Mitchell 2003; Ishizaki et al. 2012). Moreover, recent research has indicated that the relationships between global-mean SAT and global-mean precipitation differ among emission scenarios (Shiogama et al. 2010b; Frieler et al. 2011).

Although some impact and adaptation research that will be carried out to provide input for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) will use pattern scaling (Moss et al. 2010), the scenario dependence of precipitation scaling patterns among representative concentration pathways (RCPs) has not been investigated in detail. In this study, we therefore investigated the scenario dependence of precipitation scaling patterns to test the basic hypothesis of the pattern scaling approach. The scaling pattern consists of the spatial pattern of the temperature coefficient of a climate variable. We mainly focused on the temperature coefficient of aerosol loadings and the nonlinear responses of the climate system to global warming.

2. Model description

We used an atmosphere–ocean GCM developed by the Japanese research community called the Model for Interdisciplinary Research on Climate, version 5 (MIROC5; Watanabe et al. 2010). The horizontal resolutions of the atmospheric and ocean models are T85 and approximately 1°, with 40 and 49 vertical layers, respectively. Incorporated into MIROC5 is an aerosol transport-radiation model called the Spectral Radiation–Transport Model for Aerosol Species (SPRINTARS; Takemura et al. 2000, 2002, 2005) that can treat both direct and indirect effects of anthropogenic aerosols, including in particular the effects of carbonaceous matter (black carbon and organic matter) and sulfate. For each RCP there is an associated scenario of aerosol emissions. We calculated scaling patterns for three RCPs, RCP2.6 (van Vuuren et al. 2007), RCP4.5 (Wise et al. 2009), and RCP8.5 (Riahi et al. 2007), and with a twentieth-century simulation. We used the preindustrial control run to remove the influence of model drift. We concentrated our analysis on the differences between RCP8.5 and RCP2.6 because those differences were greater than...
the ones between RCP8.5 and RCP4.5. We analyzed the ensemble mean of three ensemble members for each scenario. We did not analyze RCP6.0 (Hijioka et al. 2008) because only one ensemble member is available in MIROC5.

3. Methods

a. Procedure for estimating scaling patterns

In this study, we used the method proposed by Mitchell et al. (1999) to estimate the scaling pattern. In this method, the pattern of change for a climate variable $C(x, t)$ simulated by a GCM at position $x$ and time $t$ are estimated by

\[ C^*(x, t) = \mathcal{C}(t)S(x), \]

where $C^*(x, t)$ is the approximate pattern obtained by pattern scaling, $\mathcal{C}(t)$ is the scaling factor, and $S(x)$ is the scaling pattern of a climate variable. In this study, we used decadal changes from the first to the ninth decade of the twenty-first century (2010s–2090s) as the scaling factor $\mathcal{C}(t)$. We defined the decadal changes as the differences between the averages of the current period from 1981 to 2000 and the averages of the ninth decade of the twenty-first century (2010s–2090s). The variable $S(x)$ is estimated by linear regression forced through zero; that is, $S(x)$ describes the temperature coefficient of a climate variable $C(x, t)$ at position $x$ and is equated to the regression coefficient that minimizes the root-mean-square differences between the simulated pattern $C(x, t)$ and the approximated pattern $C^*(x, t)$ as follows:

\[ S(x) = \frac{\sum_{t=1}^{9} \mathcal{C}(t)C(x, t)}{\sum_{t=1}^{9} \mathcal{C}(t)^2}. \]

b. Analysis of water and heat budgets

We analyzed water and heat budgets to investigate the causes of the dependence of precipitation scaling patterns on RCP emission scenarios. At equilibrium, the time-averaged and vertically integrated atmospheric water balance can be expressed by the following equation:

\[ M = P - E, \]

where $P$ is precipitation, $E$ is evaporation, and $M$ is the convergence of the column-integrated water vapor content in kilograms per meter squared (Joshi et al. 2008).

The global atmospheric heat budget $HB$ at the surface consists of four atmospheric heat terms: the net downward flux of shortwave radiation $S \downarrow$, the net upward flux of longwave radiation $LW$, the sensible heat flux $SH$, and the flux of latent heat $LH$ that is subsequently released to the atmosphere by the condensation of water that has evaporated from the land or ocean. This budget can be expressed by

\[ HB = S \downarrow - LW - SH - LH. \]

We analyzed water and heat budgets for the regional averages of five regions based on the two equations in this study.

4. Results and discussion

a. Relationships between the temperature coefficient of global-mean precipitation and anthropogenic aerosols

Figure 1a shows the relationship between changes in global-mean SAT and percentage changes in precipitation. Global-mean precipitation sensitivity was significantly different between RCP8.5 and RCP2.6. Shortwave feedback because of clouds in MIROC5 weakly suppressed global warming (Watanabe et al. 2010; Shiozawa et al. 2012) (Fig. 1b). However, the loadings of sulfate and carbonaceous aerosols decreased significantly with increasing global-mean SAT in both RCPs (Fig. 2), and the magnitude of the temperature coefficient of the loadings of sulfate and carbonaceous aerosols was larger in RCP2.6 than in RCP8.5. The magnitudes of the direct and indirect effects of sulfate and carbonaceous aerosols consequently decreased more in RCP2.6 than in RCP8.5 in terms of global-mean warming. This led to an increase in the net downward shortwave radiation flux with increasing global-mean SAT in RCP2.6 (Fig. 1b) because of the reduction of the direct and indirect effects of aerosols.

The magnitude of the temperature sensitivity of $S \downarrow$ was smaller in RCP8.5 compared with RCP2.6. Evaporation was less sensitive to global-mean SAT in RCP8.5 compared to RCP2.6 (Fig. 1c). Because the temperature sensitivity of downward longwave radiation was about the same in RCP8.5 and RCP2.6 (Fig. 1d), the lower temperature sensitivity of evaporation in RCP8.5 was caused by the lower temperature sensitivity of $S \downarrow$ in RCP8.5. This lower temperature sensitivity of evaporation led to a lower temperature sensitivity of precipitation.

b. Differences of precipitation scaling patterns due to differences of anthropogenic aerosol scaling patterns between RCP8.5 and RCP2.6

The temperature coefficient of sulfate, organic, and black carbon aerosol loadings was negative, and the magnitude of the temperature coefficient of sulfate aerosol loading was smaller in RCP8.5 than in RCP2.6,
particularly over the industrialized areas of the Northern Hemisphere (eastern North America, Europe, and East Asia; Fig. 3a) and the magnitude of the temperature coefficient of organic and black carbon aerosol loadings was also smaller in RCP8.5 than in RCP2.6 particularly over areas of biomass burning (the central part of South America and the Congo basin; Figs. 3b,c). The positive temperature coefficient of $D_{SY}$ was consequently smaller in RCP8.5 than in RCP2.6 over these regions (Fig. 4a).

Because the temperature coefficient of $S_D$ was smaller in RCP8.5 than in RCP2.6, the temperature coefficient of the latent heat flux was less in RCP8.5 than in RCP2.6 as well, mainly over the ocean (e.g., East Asia and North America; Fig. 4c). The smaller temperature coefficient of the latent heat flux over the ocean resulted in less of an increase of the precipitation scaling pattern over the downstream region (e.g., East Asia and North America; Fig. 5). In contrast, the magnitude of the scenario dependence of the temperature coefficient of the latent heat flux was not necessarily significant over land because the scenario dependence of the temperature coefficient of $S_D$ tended to induce a scenario dependence of the temperature coefficient of not only the latent heat flux but also SH and LW over land (Figs. 4b,d). Thus, the scenario

**Fig. 1.** The relationship between the change in global-mean SAT and (a) the percentage change in precipitation, (b) percentage change in net downward surface shortwave radiation (SSR; positive defined as downward), (c) percentage change in evaporation, and (d) percentage change in downward longwave radiation. Red circles denote RCP2.6 and blue circles denote RCP8.5. Red and blue lines indicate the regression lines for RCP2.6 and RCP8.5, respectively.

**Fig. 2.** As in Fig. 1, but for the relationship between changes in global-mean SAT and changes in aerosol loading normalized to the climatology of 1981–2000 for (a) sulfate aerosols, (b) organic carbon aerosols, and (c) black carbon aerosols.
dependence of latent heat flux was not significant over central South America (Fig. 5).

The scenario dependence of the precipitation scaling pattern was significant over the Congo basin as well as East Asia and North America. However, although the temperature coefficient of $S_\downarrow$ was smaller in RCP8.5 than in RCP2.6 because of the scenario dependence of the aerosol scaling patterns, the temperature coefficient of the latent heat flux and precipitation were larger in RCP8.5 than in RCP2.6 over the Congo basins. Thus, the scenario dependence of the precipitation scaling pattern cannot be explained by the scenario dependence of the aerosol scaling pattern over the Congo basin.

The magnitudes of the precipitation scaling patterns were larger in RCP8.5 than in RCP2.6 over some grids of Europe, South America, and North America (Fig. 5), although the anthropogenic aerosol scaling patterns were smaller in RCP8.5 than in RCP2.6. Explanations for the scenario dependence of precipitation scaling patterns at the grid scale are very complex because of large natural environmental variability. We therefore analyzed regional mean averages for the five regions. Because the temperature coefficients of the direct and indirect effects of anthropogenic aerosols were higher in RCP8.5 than in RCP2.6, the temperature coefficient of $S_\downarrow$ was also lower in RCP8.5 than in RCP2.6 over the five regions (Table 1). According to the water budget analysis, the scenario dependence of the precipitation scaling pattern was basically caused by the scenario dependence of the evaporation scaling pattern over East Asia and North America (Table 2). Over the marginal seas of the East Asian landmasses, which is inferred to be the source region for precipitation over the East Asian landmasses, the scenario dependence of the temperature coefficient of $S_\downarrow$ resulted in a scenario dependence of the temperature coefficient of the latent heat flux that (through the local scenario dependence of the temperature coefficient of the latent heat flux) contributed to a scenario dependence of the temperature coefficient of precipitation over land areas of East Asia. Although the temperature coefficient of the latent heat flux was larger in RCP8.5 than in RCP2.6 over some parts of eastern North America, in general the scenario dependence of the temperature coefficient of the latent heat flux due to the scenario dependence of the sulfate aerosol scaling pattern was significant over the ocean adjacent to eastern North America. The scenario dependence of the temperature coefficient of the latent heat flux resulted in a scenario dependence of precipitation over this region.

The small magnitude of the negative temperature coefficient of black carbon and organic carbon aerosols over the central part of South America led to a small positive temperature coefficient of $S_\downarrow$ over that region. Because the small temperature coefficient of $S_\downarrow$ induced a small temperature coefficient of not only the latent heat flux but also SH and LW, the magnitude of the scenario dependence of the temperature coefficient of the latent heat flux was not significant. As a result, the magnitude of the scenario dependence of the precipitation scaling pattern was not large among the regional means as well.
c. Causes of differences of precipitation scaling patterns between RCP8.5 and RCP2.6 induced by other factors

The temperature coefficient of water vapor convergence was larger in RCP8.5 than in RCP2.6 over Europe (Table 2). The northern part of the North Atlantic Ocean warmed more in RCP8.5 than in RCP2.6 because of the nonlinear response of the Atlantic meridional overturning circulation (AMOC) to global warming in MIROC5 (Ishizaki et al. 2012). This nonlinear response of the AMOC increased evaporation in RCP8.5 more.
A significant scenario dependence of precipitation scaling patterns over the same regions. The southern annular mode (SAM) is the dominant pattern of variability in the extratropics of the Southern Hemisphere (Trenberth et al. 2007). The trend of SAM has been projected to be positive (Meehl et al. 2007), and tropospheric jet streams and storm tracks have been projected to shift poleward (Riviere 2011).

Because the rate of stratospheric ozone recovery in the polar region of the Southern Hemisphere was smaller in RCP8.5 than in RCP2.6, the lower stratosphere was cooler in RCP8.5 than in RCP2.6 (not shown). For this reason, the rate of poleward shift of the tropospheric jet streams differed significantly between the RCPs over the Southern Hemisphere (Fig. 7c). The temperature coefficient of the poleward shift of the tropospheric jet streams was larger in RCP8.5 than in RCP2.6 over the Southern Hemisphere. Because a stronger jet stream induces stronger storm-track activity, differences of the precipitation scaling patterns were found over the midlatitudes of the Southern Hemisphere (Fig. 5).

Significant scenario dependences of precipitation were found over some parts of the Arctic and around Greenland. Ishizaki et al. (2012) indicated that the rate of increase of SAT over the regions was larger in RCP8.5 than in RCP2.6 because of the nonlinear response of sea ice and AMOC to global warming. The values of the temperature coefficient of evaporation rates over these regions were thus also larger in RCP8.5 than in RCP2.6 (Fig. 4c). The scenario dependence of the temperature coefficient of evaporation rates induced a scenario dependence of the precipitation scaling pattern over these regions.

d. Differences of precipitation scaling patterns between RCP8.5 and RCP4.5

Scenario dependences of precipitation scaling patterns were also evident between RCP8.5 and RCP4.5 (Fig. 8) over East Asia, the Congo basin, and the region around the Gulf of Guinea and the Maritime Continent; although the magnitude of the scenario dependence of the precipitation scaling pattern tended to be smaller between RCP8.5 and RCP4.5 than between RCP8.5 and RCP2.6. The scenario dependence of the precipitation scaling pattern between RCP8.5 and RCP4.5 over East Asia, the region around the Gulf of Guinea, and the Maritime Continent can be explained by the scenario

| Table 1. Results of heat budget analysis over East Asia (EA; 20°–45°N, 100°–160°E), Europe (EU; 35°–65°N, 10°W–90°E), eastern North America (NA; 25°–50°N, 40°–110°W), central parts of South America (SA; 0°–30°S, 45°–75°W), and the Congo basin (CB; 5°S–15°N, 10°–30°E). All values are the differences between RCP8.5 and RCP2.6. |
|----------------|---|---|---|---|---|
| ΔS/ΔSAT (W m⁻² K⁻¹) | -3.1 | -5.8 | -2.6 | -1.5 | -2.3 |
| ΔLW/ΔSAT (W m⁻² K⁻¹) | -0.6 | -2.7 | -0.8 | -0.6 | -1.4 |
| ΔHI/ΔSAT (W m⁻² K⁻¹) | -1.9 | -1.1 | -0.9 | -0.6 | 0.0 |
| ΔSH/ΔSAT (W m⁻² K⁻¹) | -0.3 | -2.0 | -0.6 | -0.4 | -1.0 |

| Table 2. As in Table 1, but for results of water budget analysis. |
|----------------|---|---|---|---|---|
| ΔP/ΔSAT (mm day⁻¹ K⁻¹) | -0.09 | 0.0 | -0.03 | -0.01 | 0.04 |
| ΔE/ΔSAT (mm day⁻¹ K⁻¹) | -0.07 | -0.04 | -0.03 | -0.02 | 0.0 |
| (ΔP - ΔE)/ΔSAT (mm day⁻¹ K⁻¹) | -0.02 | 0.04 | 0.0 | 0.01 | 0.04 |
dependence of the evaporation scaling pattern (Fig. 9) due to the scenario dependence of the scaling patterns of sulfate and carbonaceous aerosols (Fig. 10).

The scenario dependence of the scaling pattern of precipitation over the Congo basin is induced by the scenario dependence of the African Walker circulation (not shown). Thus, the scenario dependence of the precipitation scaling pattern between RCP8.5 and RCP2.6 can be explained by the factors responsible for the differences between RCP8.5 and RCP2.6; although the characteristics of the RCP2.6 emission scenarios are distinctively different from the corresponding characteristics of the other RCPs due to the suppression of the global-mean temperature increase by 2°C (van Vuuren et al. 2007).

The analysis in this study was based on the results of only one global climate model, but the differences in aerosol concentrations (Forster et al. 2007), the extent of sea ice melting, and the reduction of the AMOC (Meehl et al. 2007) in future projections remain very large among AOGCMs. Investigations of the dependence of precipitation scaling patterns on the choice of AOGCM are required in future work.

5. Summary

Pattern scaling will play an important role in the assessment of some of the environmental impacts to be addressed in the IPCC AR5. The basic assumption of this approach is that there is a scaling pattern common to all emission scenarios. However, previous research has indicated that the responses of global-mean precipitation changes to global-mean SAT changes depend on emission scenarios because of differences in rates of change of aerosol emissions (Shiogama et al. 2010b; Frieler et al. 2011). In this study, we investigated the scenario dependence of precipitation scaling patterns, the focus being on the scenario dependence introduced by the scenario dependence of the scaling patterns of sulfate and carbonaceous aerosols.

The scenario dependence of the scaling pattern of aerosols induced a scenario dependence of the scaling pattern of the temperature coefficient of $S_Y$ but did not necessarily induce a scenario dependence of the precipitation scaling pattern. When the scenario dependence of the scaling pattern of aerosols occurred over the ocean, the scenario dependence of the temperature coefficient of $S_Y$ induced a scenario dependence of the temperature coefficient of latent heat. As a result, the scenario dependence of the precipitation scaling pattern tended to occur over the immediate region and downstream regions. Contrariwise, when the scenario dependence of the aerosol scaling patterns occurred over land, the scenario dependence of the temperature coefficient of $S_Y$ induced scenario dependences of the temperature coefficient of not only latent heat but also LW and SH. Consequently, the scenario dependence of the temperature coefficient of latent heat was weak, and the scenario dependence of the precipitation...
scaling pattern therefore did not tend to be statistically significant. This may be related to the limited moisture availability for evaporation over land as opposed to the ocean.

Projections of precipitation are important inputs to assessments of the impacts of climate change and related adaptation research. Scientists who study these topics need to pay attention to the scenario dependence of the scaling pattern of precipitation if the scenario dependences are important for their research. Modified approaches based on a statistical analysis of anthropogenic aerosols, as

![Scaling pattern differences between RCP8.5 and RCP2.6](image_url)
suggested by Frieler et al. (2012), would be required to offset the effects of scenario dependence. Moreover, in addition to the scenario dependence of the scaling pattern of anthropogenic aerosols, the nonlinear responses of the AMOC and sea ice melting over the Arctic to global warming and the scenario dependences of the temperature coefficient of SAM, the Hadley circulation, and the African Walker circulation are also important.

Because the differences of the global-mean SAT changes between RCP8.5 and RCP4.5 are smaller than those between RCP8.5 and RCP2.6, the scenario dependences of the scaling patterns of anthropogenic aerosols and of

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**Fig. 8.** Scaling pattern differences between RCP8.5 and RCP4.5 in the temperature sensitivity of precipitation (% K$^{-1}$). Dotted regions are statistically significant at the $\alpha = 0.05$ level ($F$ test).

**Fig. 9.** Scaling pattern differences between RCP8.5 and RCP4.5 in the temperature coefficients of (a) surface shortwave radiation (W m$^{-2}$ K$^{-1}$; positive defined downward), (b) surface longwave radiation (W m$^{-2}$ K$^{-1}$; positive defined upward), (c) latent heat (W m$^{-2}$ K$^{-1}$; positive defined upward), and (d) sensible heat (W m$^{-2}$ K$^{-1}$; positive defined upward). Colored regions are statistically significant at the $\alpha = 0.05$ level ($F$ test).
Hadley circulation and SAM between RCP8.5 and RCP4.5 were less than those between RCP8.5 and RCP2.6. As a result, the scenario dependence of precipitation tended to be less between RCP8.5 and RCP4.5 than between RCP8.5 and RCP2.6 overall. Thus, when pattern scaling is applied to an emission scenario, it is better to remove the scenario dependence by using the RCP that projects global-mean SAT changes and aerosol loadings similar to those projected by the emission scenario.

**Fig. 10.** Scaling pattern differences between RCP8.5 and RCP4.5 in the temperature coefficients of aerosol column loading for (a) annual-mean sulfate aerosol (10^{-6} kg m^{-2} K^{-1}), (b) black carbon (10^{-6} kg m^{-2} K^{-1}), and (c) organic carbon (10^{-7} kg m^{-2} K^{-1}). Colored regions are statistically significant at the $\alpha = 0.05$ level ($F$ test).

In this study, we averaged only three ensemble members. This averaging may not have removed the influences of internal variability in the climate system. Some of the dependencies that cannot be explained in this study may have been caused by the influences of internal variability. In addition, large-scale atmospheric changes resulting from other nonlinear responses in the climate system might explain the dependence of the scaling pattern of precipitation over some regions. Sensitivity experiments that remove aerosol emissions from some regions or remove some kinds of aerosols (e.g., Shindell et al. 2012; Shiogama et al. 2010a; Kawase et al. 2011) are ideal to investigate the impacts of aerosols, although these kinds of sensitivity studies require huge computer resources. In future studies, similar sensitivity experiments should be conducted. Furthermore, the findings of this study may be model dependent. Thus, the dependencies of precipitation scaling patterns among AOGCMs must be investigated in future work.

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