4.2 Relationship between a spatial pattern of future atmospheric warming and Asian dust emission

Nobumitsu Tsunematsu [1*], M. Hayasaki [1], T. Sato [2], N. Manago [1], F. Cui [1], S. Miyazawa [1], A. Kondoh [1], H. Kuze [1], K. Sakamoto [3]

[1] Center for Environmental Remote Sensing, Chiba University, Japan
[2] Faculty of Environmental Earth Science, Hokkaido University, Japan
[3] GPE-Corner, Weathernews Inc., Japan
[*] E-mail: tsunematsu@faculty.chiba-u.jp

1. Introduction

Climate model projections show spatial patterns of future atmospheric warming that will be caused by further global warming (IPCC AR4); atmospheric temperatures considerably increase in the lower troposphere at high latitudes in the Northern Hemisphere and in the upper troposphere at low-middle latitudes. This leads to future changes in the meridional and vertical atmospheric temperature distributions in the Northern Hemisphere. The meridional atmospheric temperature gradients are expected to decrease in the lower troposphere and increase in the upper troposphere. Atmospheric stabilities are expected to increase at low-middle latitudes and decrease at high latitudes.

Asian dust phenomenon is one of well-known springtime atmospheric phenomena in East Asia. Asian dust particles are emitted mainly from the Taklimakan and Gobi deserts, and then transported to Korea and Japan mainly by low-pressure systems. The Asian dust emission is frequently induced by cold air surges originating from Siberian air masses (e.g., sun et al., 2001). Therefore, the future Asian dust emission should be influenced by the large atmospheric warming in the lower troposphere at high latitudes in the Northern Hemisphere. The future changes in atmospheric stabilities are also expected to influence the Asian dust emission, because the dust emission is closely associated with atmospheric stabilities (e.g., Tsunematsu et al., 2005). Nevertheless, the number of numerical studies investigating the relationship between future global warming and Asian dust emission is still rather small. This study therefore investigated potential impacts of the spatial patterns of future atmospheric warming on Asian dust emission by conducting numerical modelexperiments.

2. Analyses of Global Climate Model Outputs

Output data from the Model for Interdisciplinary Research On Climate (MIROC V3.2-hires: K-1 model developers, 2004) were analyzed to obtain the spatial pattern of future atmospheric warming and their relation to other atmospheric variables. The MIROC model is one of global-scale climate models that are capable of reproducing past climate and predicting future climate. This model has 23 vertical levels and T106 horizontal resolution (approximately 120 km, 1.125° x 1.125°).

In this study, the MIROC output data derived from results of the 20th Century Climate in Coupled Models (20C3M) experiment and the 21st century climate projection based on the Special Report on Emission Scenario (SRES) A1B were used to obtain “recent climate” for the period of 1991-2000 and “future climate” in 2091-2100, respectively. Using the monthly mean data, differences in atmospheric temperatures, geopotential heights, and u-v wind components between the future and recent climate were calculated for each grid of the MIROC model. Sato et al. (2007) named the differences “Global Warming Monthly mean Differences (GWMDs)”. Months of the data used for the calculations of the GWMDs were restricted to March and April when the frequency of the Asian dust outbreaks is considerably higher than other months. The March and April monthly mean data were averaged before calculating the GWMDs. The 50-130°E zonal mean GWMDs at latitudes between 20°N and 80°N were prepared for each vertical level of the MIROC model (Figure 1) to downscale the future changes in the meridional and vertical distributions of atmospheric temperatures, geopotential heights, and horizontal wind components into dust simulations by a regional-scale atmospheric model.

3. Dust Simulations by WRF/Chem

The advanced research version of the Weather Research and Forecasting (WRF) modeling system V3.1 (Skamarock et al., 2008) was used for numerical experiments on dust. This modeling system provides an atmospheric chemistry model (WRF/Chem V3.1: Grell et al., 2005) that is capable of simulating the regional-scale movements of various gases and aerosol particles. This study altered source codes of WRF/Chem to simulate emission, advection, dispersion, and deposition of soil dust with the Particulate Matter up to 10 µm in size (PM10) only, after assuming the PM10 soil dust to be Asian dust particle.

Prior to the main numerical experiments in this study, a significant Asian dust event that occurred during the period from March 29 to April 2, 2007 was simulated by using the WRF-Chem model as the pre-experiment. The pre-experiment was conducted to confirm whether the WRF-Chem model could be applied to dust simulations. A brief outline of this Asian dust event is that the dust particles were emitted mainly from the Gobi and Taklimakan deserts and then transported to a considerably large area of East Asia including the megacities, such as Shanghai, Seoul, and Tokyo (e.g., Tsunematsu et al., 2009). In the pre-experiment, a calculation domain was given by 160 x 84 horizontal grids centered at 40°N/90°E with the grid interval of 40 km. The number of the vertical layers was set at 30. The 6-hourly global analysis data from the National Centers for Environmental Prediction-FiNaL (NCEP-FNL), which has a 1.0° x 1.0° horizontal resolution, were used for the initial and boundary conditions. An initial time of the 72 hours numerical integration was set at 0000 Universal Time Coordinated (UTC) March 29, 2007. Potential areas of the soil dust emission were determined by the U.S. Geological Survey (USGS) land covers, which are categorized into barren and sparsely vegetated, shrubland, and grassland. The particles were emitted from not the ground surface but the first level of the model in this study. The height of the first level is approximately 29 m above ground level (AGL). The 29 m height difference can be disregarded because the calculation domain has a horizontal scale of several thousand kilometers. The hourly emission mass fluxes of the PM10 soil dust at each grid of the model were calculated by equations presented by Mukai et al. (2004). Also, the emission mass flux was set at zero when the model grid was covered with snow. The soil moisture content and snow cover are simulated by using the NCEP-FNL data. The hourly emission of the soil particles started at the initial time plus 6 hours due to the spin-up of the model. In addition to the emission processes, the model includes calculations of both dry and wet deposition processes of the soil particles.

To show the reproducibility of the dust simulations, the spatial and temporal distributions of the simulated PM10 soil dust mass concentrations obtained from results of the pre-experiment were compared with observations of PM10 and suspended particulate matter (SPM) mass concentrations near the ground surface in Japan, located at far distance from the Asian dust sources.

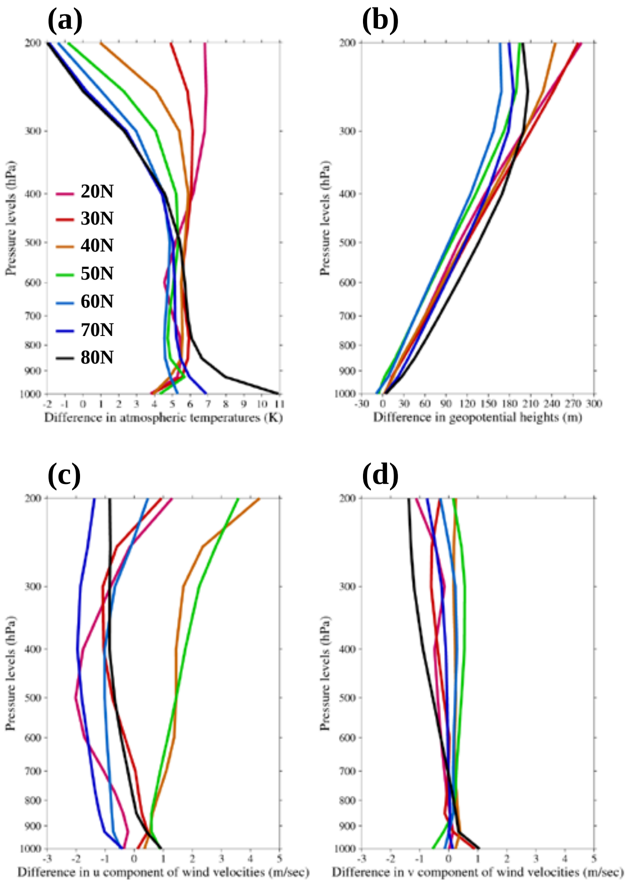

Fig. 1 Vertical profiles of the 50°E-130°E zonal mean "Global Warming Monthly mean Differences (GWMDs)" at latitudes between 20°N and 80°N of (a) atmospheric temperatures (K), (b) geopotential heights (m), (c) u component of wind velocities (m s^{-1}), and (d) v component of wind velocities (m s^{-1}).

The PM10 and SPM observation data were provided by the acid deposition monitoring NETwork in East Asia (EANET: http://www.eanet.cc/), and the Ministry of the Environment and local governments of Japan, respectively. While the PM10 data are collected from a few sites, the SPM observations are conducted at numerous sites on the Japanese Islands (Figures not shown here).

4. Pseudo Global Warming Experiments

The main numerical experiments for investigating potential impacts of the spatial patterns of future atmospheric warming on Asian dust emission were performed with another calculation domain given by 150 x 150 horizontal grids with the center of 50°N/90°E and the grid interval of 40 km. This domain is almost centered on the Asian dust sources, i.e., the arid and semi-arid regions in China and Mongolia. Also, the domain includes a large area at high latitudes where Siberian air masses develop and release cold air surges that frequently induce Asian dust emission. In the main experiments, the option of “heat and moisture fluxes from the surface” in the WRF model was turned off to remove interaction between the atmosphere and surface because this study did not consider future changes in the surface conditions. Other settings of the main experiments are the same as those of the pre-experiment.

First, we randomly selected the three significant Asian dust outbreak events, which occurred on April 5, 2002, April 16, 2003, and March 31, 2007, and then simulated those dust outbreaks as the control runs (CTLs). The initial times of the CTLs were set at 0000 UTC April 3, 2002, 0000 UTC April 14, 2003, and 0000 UTC March 29, 2007, respectively, prior to the 72 hours numerical integration. Second, the vertical profiles of the zonal mean GWMDs of atmospheric temperatures, geopotential heights, and u-v wind components at latitudes between 20°N and 80°N, described in Section 2, were added to each variable of the 6-hourly NCEP-FNL data in proportion to the latitudes and pressure levels in order to update the initial and boundary conditions of the CTLs. Third, the updated initial and boundary conditions were used to execute the “pseudo global warming runs (PGWs)”. In the PGWs, relative humidity in the future climate was assumed to be equal to that in the recent climate because atmospheric warming can increase both the absolute amount of water vapor and the saturation vapor pressure, preventing relative humidity from largely changing. Finally, the future changes in Asian dust emission were analyzed by comparing results of the PGWs with those of the CTLs.

Many previous studies adopted this dynamical downscaling method to perform numerical experiments called the “pseudo global warming experiments” [e.g., Sato et al., 2007; Kawase et al., 2009]. This downscaling method allows the spatial patterns of future atmospheric warming, derived from output data from the coarse resolution global-scale climate model (MIROC), to impact on the dust simulations by the fine resolution regional-scale atmospheric model (WRF/Chem). We can quantitatively estimate the impacts of the spatial patterns of future atmospheric warming on Asian dust emission fluxes by executing the CTL and PGW under the same background atmospheric condition and the same dust event. These are difficult for traditional dynamical downscaling methods that directly give grid point values of global-scale climate model projections to regional-scale model simulations.

Results of the experiments showed that the soil dust emission fluxes in the main Asian dust sources, i.e., the Taklimakan and Gobi deserts, decrease markedly in the future climate. In all of the three dust outbreak events, cold air outbreaks that induce Asian dust emission originated from the vicinities of Lake Baikal, the western part of Mongolia, and the Dzungaria Basin (Figures not shown here). Based on the cold air outbreak routes, we can discuss a dynamical mechanism of the future decreases in the soil dust emission fluxes in the Taklimakan and Gobi deserts. Figure 2 shows mean distributions of differences in the daily total emission mass fluxes of the PM10 soil dust, the daily total column-integrated mass concentrations of the PM10 soil dust, the daily mean sea level pressures (SLPs), and the daily mean surface air temperatures between the PGWs and CTLs, averaged over the three days: April 5, 2002, April 16, 2003, and March 31, 2007. The large increases in SLPs in the Taklimakan Desert and the small SLP changes in a region ranging from the vicinity of the Dzungaria Basin to the western part of

Mongolia reduce the SLP gradients between the two areas (Fig. 2c). Similarly, the large SLP increases in the eastern part of the Gobi Desert and the small SLP changes in a region ranging from the vicinity of Lake Baikal to the western part of Mongolia reduce the SLP gradients between those areas (Fig. 2c). The former SLP gradient reduction results in a weakening of the cold air surges intruding into the Taklimakan Desert, which usually move across the Tienshan Mountains or along the eastern rim of the mountains (e.g., Tsunematsu, 2005). The latter reduction leads to a weakening of the cold air surges moving to the Gobi Desert. The resultant decreases in surface wind velocities in the Taklimakan and Gobi deserts (Figures not shown here) cause the remarkable reduction in the soil dust emission fluxes in those deserts (Fig. 2a). It is thus found that 1) the small SLP changes in the region located to the north of the main Asian dust sources (the Taklimakan and Gobi deserts) and 2) the large SLP increases in the main dust sources are two important factors in decreasing the future dust emission fluxes. Incidentally, the small SLP changes corresponded to the large increases in surface air temperatures (Figs. 2c-d).

5. Summary

Potential impacts of the spatial patterns of future atmospheric warming on the Asian dust emission were investigated by performing the pseudo global warming experiments for the three significant Asian dust outbreak events. After the three events were reproduced by using WRF/Chem as the control runs, the initial and boundary conditions of the control runs were updated by adding the vertical profiles of the 50-130°E zonal mean GWMDs of atmospheric temperatures, geopotential heights, and u-v wind components at latitudes between 20°N and 80°N in order to carry out the pseudo global warming runs. The GWMDs were calculated from the MIROC outputs of the 20C3M experiment and the SRES-A1B 21st century climate projection for the periods of March and April in 1991-2000 and 2091-2100, respectively. Results of the experiments showed that the future soil dust emission fluxes in the main Asian dust sources decrease markedly, compared with the emission fluxes in the recent climate. The SLPs in the main dust sources largely increased in the future climate condition. However, the future SLP changes in the region located to the north of the main dust sources were small. The future meridional SLP gradients between the two areas therefore decreased, weakening the cold air surges and also Asian dust emission. This dynamical mechanism can lead to reduction in the future dust emission.

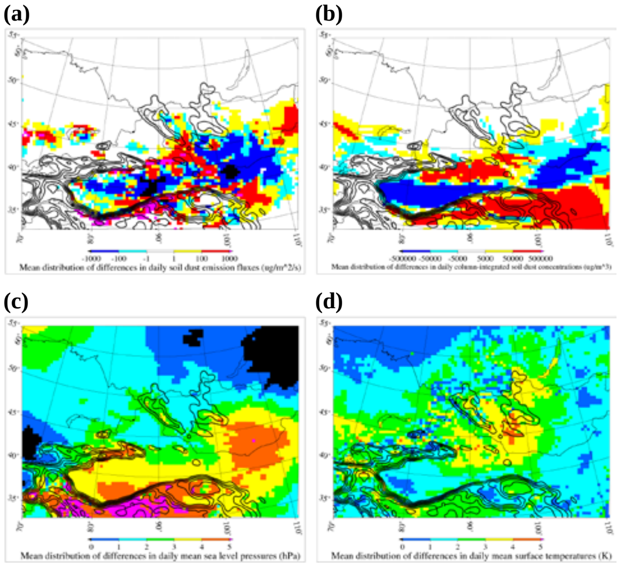

Fig. 2 Mean distributions of the differences in (a) the daily total emission mass fluxes of the PM10 soil dust (μg $m^{-2} s^{-1}$), (b) the daily total column-integrated mass concentrations of the PM10 soil dust (μg m^{-2}) in the atmosphere, (c) the daily mean sea level pressures (hPa), and (d) the daily mean surface air temperatures (K) between the PGWs and CTLs, averaged over the three days: April 5, 2002, April 16, 2003, and March 31, 2007.

Acknowledgements

This study was supported by Grant-in-Aid for Scientific Research of Ministry of Education, Culture, Sports, Science and Technology of Japan (No.20403008). The MIROC model data were provided by a project of Formation of a virtual laboratory for diagnosing the earth's climate system with climate study-related research centers of University of Tokyo, Tohoku University, Chiba University, and Nagoya University. The numerical model experiments were performed by utilizing the T2K-Tsukuba system installed in Center for Computational Sciences, University of Tsukuba.

References

Grell, G.A, S.E. Peckham, R. Schmitz, S.A. McKeen, G. Frost, W.C. Skamarock, and B. Eder (2005), Fully coupled “online” chemistry within the WRF model, *Atmos. Environ.*, *39*, 6957-6975.

K-1 model developers (2004), K-1 coupled GCM (MIROC) description [Hasumi, H., and S. Emori (eds.)], K-1 Technical Report, 1, 34pp. (available from the Center for Climate System Research, University of Tokyo)

Kawase, H., T. Yoshikane, M. Hara, F. Kimura, T. Yasunari, B. Ailikun, H. Ueda, and T. Inoue (2009), Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downscaling method, *J. Geophys. Res.*, *114*, D24110, doi:10.1029/ 2009JD011803.

Mukai, M., T. Nakajima, and T. Takemura (2004), A study of long-term trends in mineral dust aerosol distributions in Asia using a general circulation model, *J. Geophys. Res.*, *109*, D19204, doi:10.1029/2003JD004270.

Sato, T., F. Kimura, and A. Kitoh (2007), Projection of global warming onto regional precipitation over Mongolia using a regional climate model, *J. Hydrol.*, *333*, doi:10.1016/j.jhydrol.2006.07. 023.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X. Huang, W. Wang, and J. G. Powers (2008), A description of the Advanced Research WRF Version 3, NCAR/TN-475+STR, 113 pp.

Sun, J., M. Zhang, and T. S. Liu (2001), Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960-1999: Relations to source area and climate, *J. Geophys. Res.*, *106*, 10,325-10,333.

Tsunematsu, N. (2005), Observed dust storm in the Taklimakan Desert on April 13, 2002, *Sci. Online Lett. Atmos.*, *1*, 21-24.

Tsunematsu, N., T. Sato, F. Kimura, K. Kai, Y. Kurosaki, T. Nagai, H. Zhou, and M. Mikami (2005), Extensive dust outbreaks following the morning inversion breakup in the Taklimakan Desert, *J. Geophys. Res.*, *110*, D21207, doi:10.1029/ 2005JD005994.

Tsunematsu, N., H. Iwai, S. Ishii, M. Yasui, Y. Murayama, and K. Mizutani (2009), Influence of surface-based stable layer development on Asian dust behaviour over Tokyo, *Boundary Layer Meteorol.*, *131*, 263-275.