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Contributions of the Pollutant Emission in South Korea to the Aerosol Concentrations and Depositions in Asia

Soon-Ung Park, In-Hye Lee, Anna Choe, and Seung Jin Joo

Center for Atmospheric and Environmental Modeling, Seoul, Korea

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Abstract: The spatial distributions of annual mean concentrations and the annual total depositions of the Asian dust (AD) aerosol and the anthropogenic aerosol (AA) in 2010 are investigated with pollutant emissions over the whole model domain of Asia and without the pollutant emission from South Korea using the Aerosol Modeling System (AMS) that is modified from the Asian Dust Aerosol Model2 (ADAM2) and the Community Multi-Scale Air Quality (CMAQ) modeling System. The annual mean surface aerosol concentrations in Asia are found to affect a wide region as a complex mixture of AA and AD aerosols. However, the contribution of the pollutant emission from South Korea is found to be limited to the neighboring regions. The annual total aerosol deposition in Asia is 485.2 Tg. However, the contribution due to the pollutant emission from South Korea is about 1.9 Tg, suggesting of no significant contribution to the environment.

Key words: ADAM2, AMS, CMAQ, deposition, South Korea

1. Introduction

Atmospheric aerosols can affect not only the human health (Bates et al., 1966; Dockery et al., 1992; 1993; Binkowski and Shankar, 1995; Balásházy et al., 2003; Yadav et al., 2003; Davis et al., 2010; Perez et al., 2008; Jiménez et al., 2010; Sajani et al., 2010; Cowie et al., 2010; Chan et al., 2008; Middleton et al., 2008) but also environment including by scattering and absorbing radiation, altering cloud lifetime and reflectance (Miller and Tengen, 1998), reducing visibility and diminishing the aesthetic scenery (IPCC, 1996; Jacobson, 2001; Lai and Sequerira, 2001; Kaufman et al., 2002; Watson, 2002; Chang and Park, 2004; Crutzen 2004; Penner et al., 2004; Park et al., 2005; Jung et al., 2009). Depositions of aerosols can affect significantly the terrestrial and marine eco-systems (Baker and Croot, 2010).

Asia is a major source of both natural aerosol (Asian dust) and anthropogenic aerosols over the Northern Hemisphere. Asian dust that is a typical example of mineral aerosol occurs in northern China and Mongolia more frequently during the spring season (Gao et al., 2000; Husar et al., 2001; In and Park, 2003; Park and In, 2003; Park and Lee, 2004; Yu et al., 2011). Anthropogenic aerosols that are mainly originated from human activities and the formation by gas to aerosol conversion of pollutants have an increasing trend due to the rapid economic expansion in many Asian countries (Chun and Lim, 2004; Lee et al., 2006; Kim et al., 2008; Park et al., 2012). Therefore tropospheric aerosols in Asia are the complex mixture of various aerosols such as Asian dust (AD) and anthropogenic aerosols (AA) from variety of sources (Park et al., 2012). Of which the submicrometer particles that are formed in the atmosphere (Seinfeld, 1986; Warneck, 1988; Finlayson-Pitts and Pitts Jr., 2000), strongly influence the occurrence frequencies of the haze and/or mist events in East Asia. In fact a wide swath of central and eastern China experienced several days of the worst air pollution the country has seen in recent memory, with dense haze covering several provinces including Beijing, Hebei, Tianjin, Shandong, Henan, Jiangsu, Anhui and Hubei from 11 to 16 January 2013 (China Daily). These events have been transported downwind regions causing a prolonged haze event with high aerosol concentrations of exceeding 200 $\mu g\ m^{-3}$ over Korea on 12 to 14 January and more than 50 $\mu g\ m^{-3}$ in parts of Japan from 13 to 15 January 2013. Another severe smog event that occurred during the spring festival holiday in China (17 February 2013) has caused the closures of 10 highways in Hebei and many flights cancelations and delays at the Beijing Capital International airport. Recent high occurrence frequencies of hazardous environmental events such as smog, haze, mist fog and dust events in association with high aerosol loadings in East Asia require some mitigation measures of the aerosol loadings.

Recently Park et al. (2012) have developed the Aerosol Modeling System (AMS) that is composed of the Asian Dust Aerosol Model2 (ADAM2) for the Asian dust aerosol modeling and the Community Multi-scale Air Quality (CMAQ) model (Version 4.7.1) for the anthropogenic aerosol modeling to predict high aerosol concentration events in Asia. This model has been used to simulate dense haze events occurred in May 2010 (Park et al., 2013a) and in January 2013 (Park et al., 2013b) in East Asia and found to simulate successfully these events.

The purpose of this study is to examine the spatial distributions of Asian dust and anthropogenic aerosols and their depositions simulated by the Aerosol Modeling System (AMS) with the use of pollutants emissions in Asia (whole model

Corresponding Author: Soon-Ung Park, Center for Atmospheric and Environmental Modeling, Byuksan 1-cha Digital valley Rm. 1011-2, Guro-dong, Guro-gu, Seoul 151-775, Korea.
E-mail : supark@snu.ac.kr

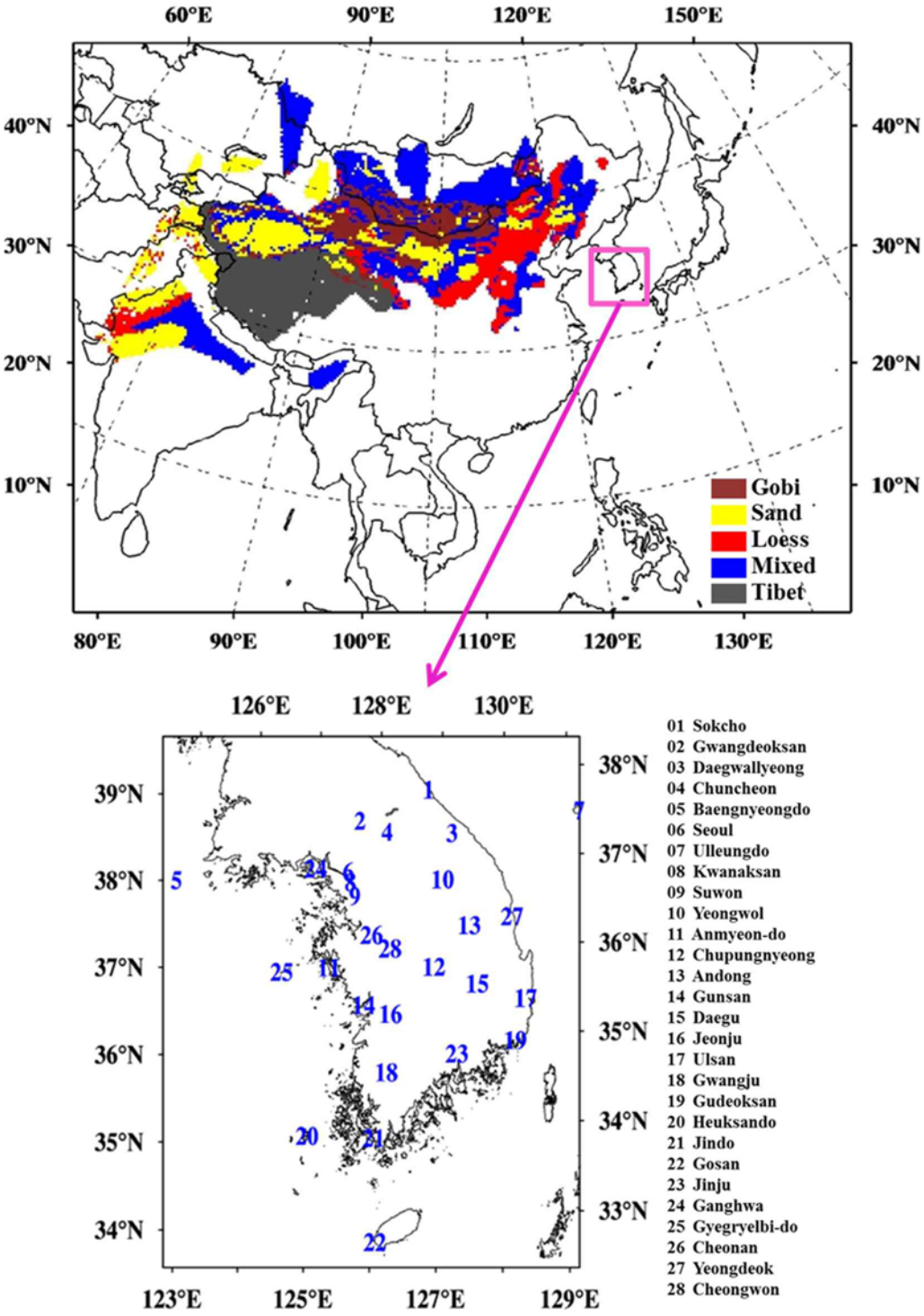

Fig. 1. The model domain and the geographical distribution of the Asian dust source region delineated by the surface soil types (Gobi; Sand; Loess; Mixed; Tibet). The enlarged South Korea map is shown with the indication of 28 PM_{10} monitoring sites.

domain) and without the pollutant emission from South Korea for the year 2010. The result will enhance our understanding on the air pollutant emission reduction strategies for the sustainable environment in Asia.

2. Model descriptions

a. Meteorological model

The meteorological model used in this study is the fifth

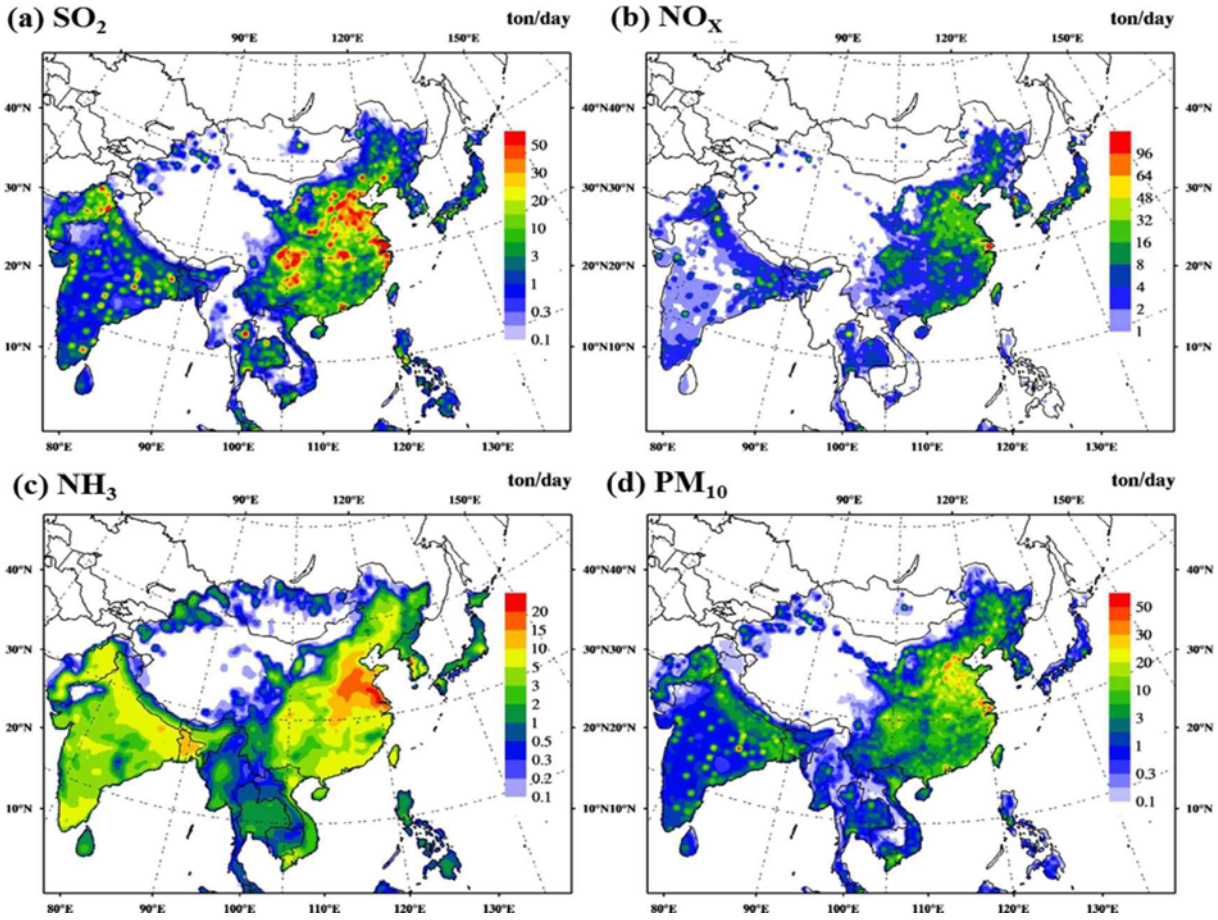

Fig. 2. Spatial distributions of emission rate (t day^{-1} grid^{-1}) of (a) SO_2, (b) NO_X, (c) NH_3 and (d) PM_{10} on May 2006 in the Asian domain (1 grid: 27 × 27 km^2).

generation mesoscale model of non-hydrostatic version (MM5; Pennsylvania State University / National Center for Atmospheric Research) defined in the x, y and σ coordinate (Grell et al., 1994; Dudhia et al., 1998). The model domain (Fig. 1) has the horizontal resolution of 27 × 27 km^2 with 30 vertical layers in the Asian region. The NCEP FNL operational global analysis data in a 1.0 × 1.0 degree grid are used for the initial and lateral boundary conditions for the model.

b. Aerosol Modeling System (AMS)

The Aerosol Modeling System (AMS) is composed of the Asian Dust Aerosol Model2 (ADAM2; Park et al., 2010) for the Asian dust aerosol modeling and the Community Multiscale Air Quality (CMAQ) Version 4.7.1 modeling system for the anthropogenic aerosol modeling with emission data of pollutants (SO_2, NO_X, VOC, CO, NH_3, BC, OC and PM_{10}) in the model domain. The AMS model uses the ADAM2 model and the CMAQ model jointly with the same grid scheme of the meteorological model (MM5).

(1) ADAM2

The ADAM2 model is an Eulerian dust transport model that includes the specification of the dust source regions delineated by the statistical analysis of the World Meteorological Organization (WMO) 3 hourly reporting dust data and statistically derived dust emission conditions in Sand, Gobi, Loess and Mixed surface soil in the model domain (Fig. 1). The model uses the suspended particle-size distribution parameterized by the several log-normal distributions in the source regions, based on the parent soil particle-size distributions with the use of the concept of the minimally and fully dispersed particle-size distribution (Gomes et al., 1990; Lu and Shaw, 1999; Shao et al., 2002; Park and Lee, 2004). It has 11-size of bins with near the same logarithm interval for particles of 0.15-35 μm in radius (Park and In, 2003; Park and Lee, 2004). The model has a temporally varying emission reduction factors derived statistically using the normalized difference vegetation index (NDVI) in the different surface soil types in the Asian dust source region. The detailed description of the model is given in Park et al. (2010).

(2) CMAQ model

The U.S. Environmental Protection Agency (EPA) Community Multiscale Air Quality (CMAQ) modeling system is a three-dimensional eulerian atmospheric chemistry and transport

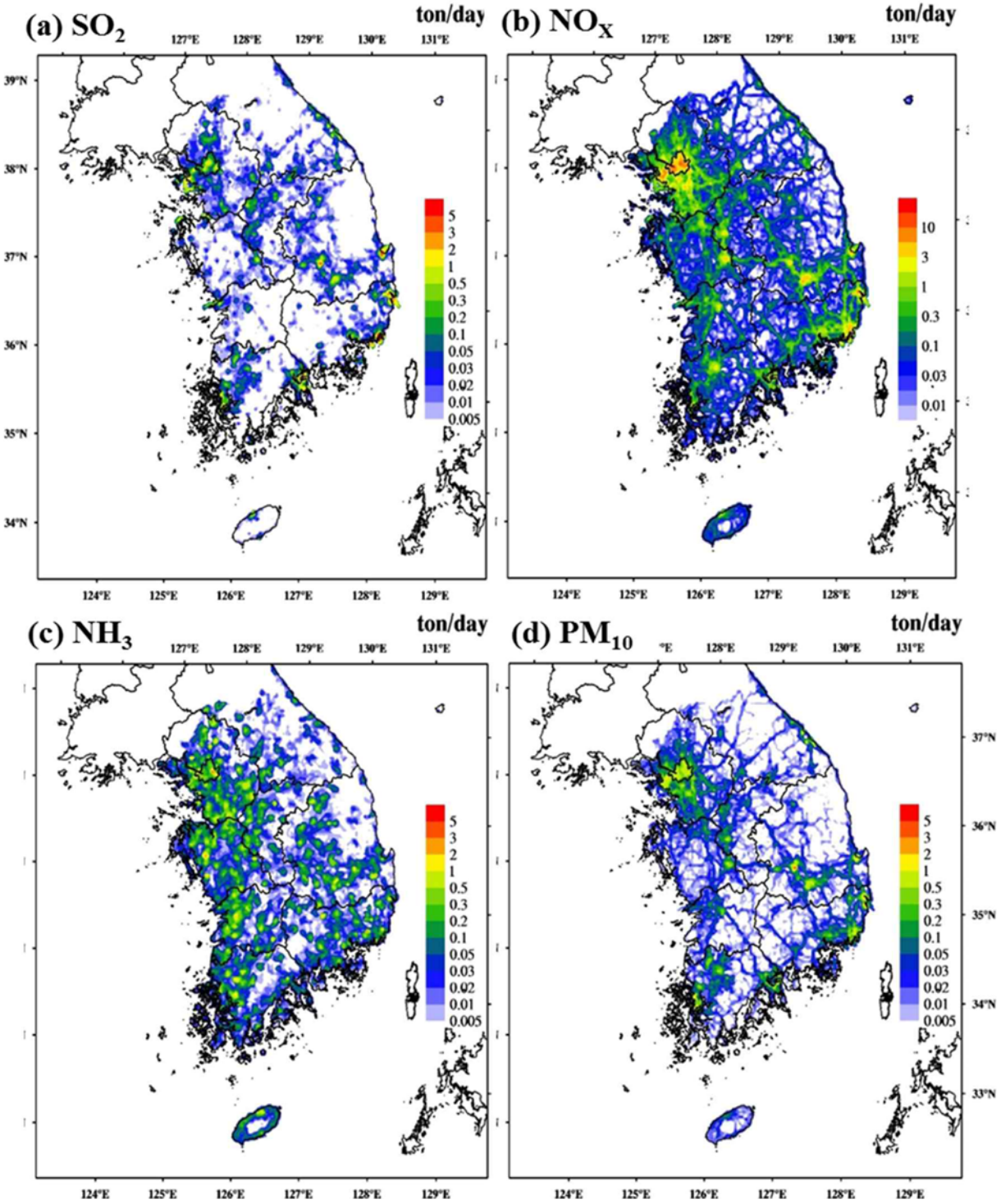

Fig. 3. Spatial distributions of emission rate (t day^{-1} grid^{-1}) of (a) SO_2, (b) NO_X, (c) NH_3 and (d) PM_{10} on May 2007 in the South Korean domain (1 grid: 27 × 27 km^2).

modeling system that simulates airborne pollutants, ozone concentration, particulate matters, visibility, and acidic and nutrient pollutant species throughout the troposphere (University of North Carolina, 2010). The aerosol component of the CMAQ Version 4.7.1 model has the particle size distribution as the superposition of three lognormal subdistributions, called modes. Fine particles with diameters less than 2.5 μm ($PM_{2.5}$) are represented by two subdistributions called the Aitken and accumulation modes. The Aitken mode includes particles with diameters up to approximately 0.1 μm

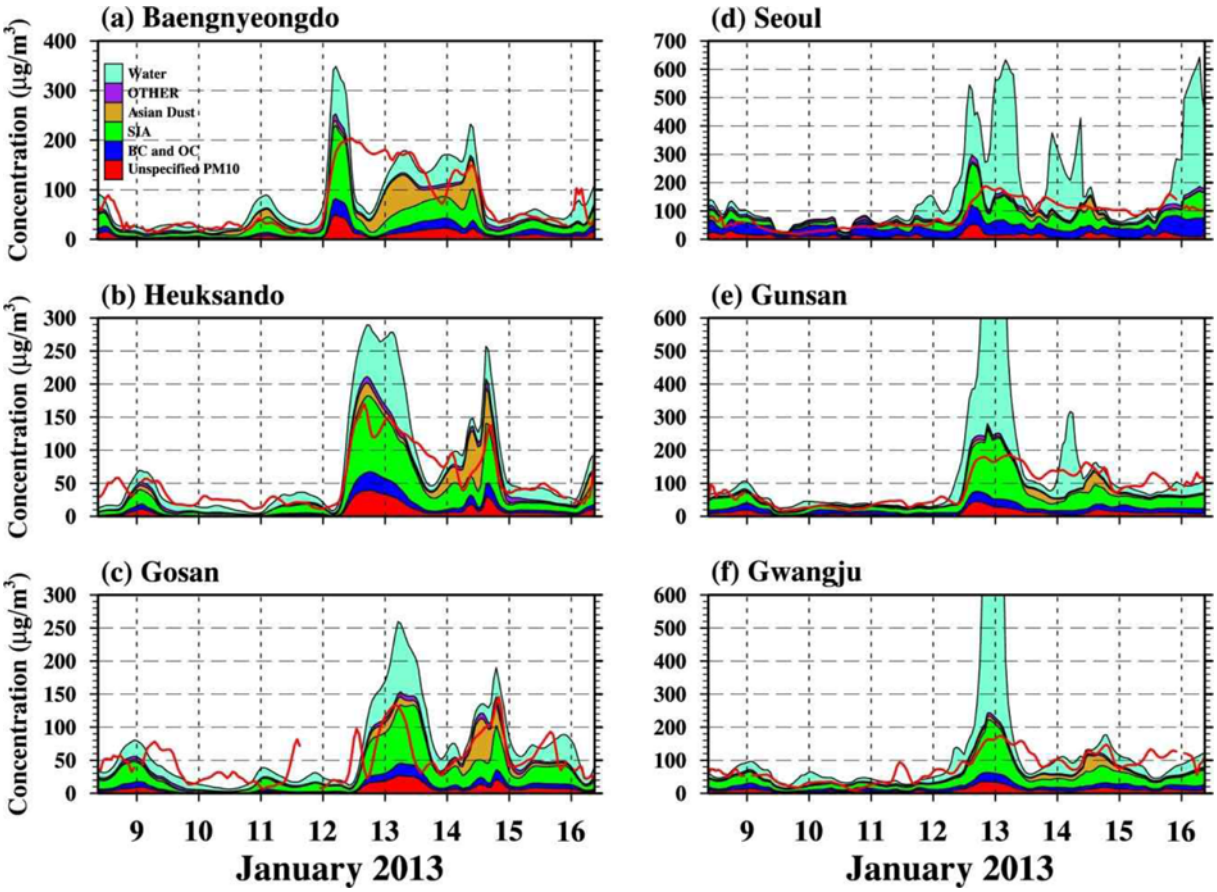

Fig. 4. Time series of hourly mean observed (red line) and modeled (shaded colors for various aerosols) PM_{10} concentration (μg m^{-3}) at (a) Baengnyeongdo, (b) Heuksando, (c) Gosan, (d) Seoul, (e) Gunsan and (f) Gwangju in South Korea for the period of 0900 LST 8 to 0900 LST 16 January 2010. Model simulated concentrations of the water droplet (Water), Sea salt and Secondary organic aerosol (OTHER), Asian dust ( ), Secondary Inorganic Aerosol (SIA), Black Carbon and Organic Carbon (BC and OC), Anthropogenically emitted PM_{10} (Unspecified PM_{10}) are indicated.

for the mass distribution and the accumulation mode covers the mass distribution in the range from 0.1 to 2.5 μm. The coarse mode covers the mass distribution in the range from 2.5 to 10 μm. The model includes the processes of coagulation, particle growth by the addition of mass and new particle formation (Binkowski and Roselle, 2003).

(3) Emission data

Air pollutant emissions in Asia (Fig. 2) in the year 2006 are obtained from the Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) that includes all major anthropogenic sources (Zhang et al., 2009). More than 60% of the total Asian anthropogenic emissions are contributed by China. The high pollutant emissions in eastern China in Fig. 2 are associated with heavy industrial activities in this region.

Air pollutant emissions in South Korea in the year 2007 are obtained from the Clean Air Policy Supporting System (CAPSS, Korea Ministry of Environment) in a 3×3 km^2 grid scheme (Fig. 3). These emission data over South Korea are regridded in a 27×27 km^2 grid scheme for the simulation of aerosols in the model. To examine the contribution of the pollutant emission from South Korea to the distributions of aerosol concentrations and depositions in the model domain, these emission data (CAPSS data) are excluded but including all emissions in other regions for the model simulation.

3. Results of the model simulation

a. Comparison of observed and simulated aerosol (PM_{10}) concentration over South Korea

The Aerosol Modeling System (AMS) has been employed to simulate concentrations of PM_{10} for the whole year of 2010 in the Asian domain (Fig. 1).

Figure 4 shows the time series of the model simulated aerosol compositions of PM_{10} and the monitored PM_{10} concentrations at 6 monitoring sites over Korea (Fig. 1) for the period of 8-16 January 2010. The model simulated PM_{10} includes all kinds of aerosols such as secondary inorganic aerosol (SIA; SO_4^{2-}, NO_3^-, NH_4^+), total carbon (BC, OC), Sea salt, together with secondary organic carbon (OTHER), emitted unspecified PM_{10}, Asian dust, and water droplet (WATER). The model simulates

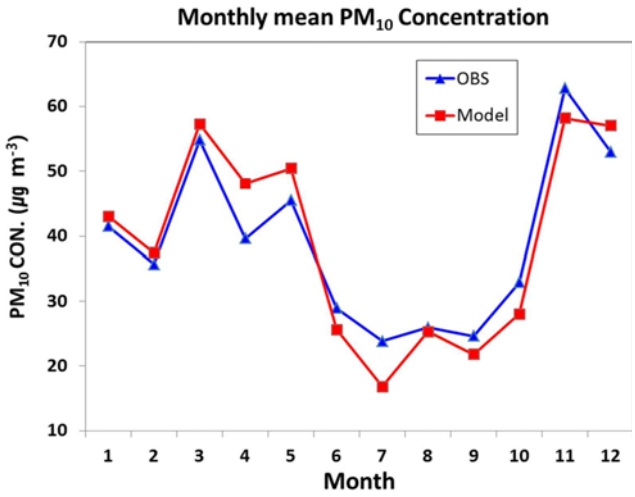

Fig. 5. Temporal variations of the observed (—▲—) and modeled (—■—) monthly mean PM_{10} concentrations (μg m^{-3}) averaged over South Korea with the use of hourly monitored and simulated data at 28 monitoring sites.

quite well the total PM_{10} concentration (sum of all aerosol species except for WATER) compared with the observation (red line). The high aerosol concentration occurred for the period from 12-14 January 2010 at all sites (Figs. 4a-f) is a mixture of anthropogenic aerosols including SIA (SO_4^{2-}, NO_3^-, NH_4^+), OC, BC and emitted PM_{10} and the natural aerosols such as Asian dust, Sea salt and water droplets. Among anthropogenic aerosols, the secondary inorganic aerosols (SIA) are predominated throughout the analysis period (Figs. 4a-f), suggesting the importance of pollutants emission of SO_2, NO_2 and NH_3 that are precursors of SIA. It is worthwhile to note that the monitored aerosol concentration does not include water droplet so that the model simulated concentration without water droplet should be compared with the monitored aerosol concentration.

The model simulated hourly mean PM_{10} concentrations at 28 monitoring sites over South Korea (Fig. 1) are compared with their corresponding monitored ones and then averaged to get area averaged PM_{10} concentration over South Korea. These data are used to get the monthly averaged PM_{10} concentration over South Korea.

Figure 5 shows modeled and monitored monthly mean surface PM_{10} concentrations averaged over South Korea with the use of data at 28 monitoring sites (Fig. 1). Some quantitative performance statistics of AMS are given in Table 1. The model simulates quite well the observed seasonal trend of the PM_{10} concentration. However it slightly overestimates PM_{10} concentration in winter and spring with a bias (BIAS) of 5.4 μg m^{-3} and a mean normalized BIAS of 12% but it slightly underestimates PM_{10} concentration in summer with a BIAS of −4.5 μg m^{-3} and a mean normalized BIAS of −14%. Consequently, the modeled annual mean PM_{10} concentration averaged over South Korea (39.7 μg m^{-3}) is almost the same as that of the monitored one (39.3 μg m^{-3}). The annual mean root mean square error (RMSE) of the model is 9.2 μg m^{-3} and the normalized mean square error is 5.5% (Table 1), suggesting the potential usefulness of the present model (AMS) for the study of temporal distributions of aerosols in Asia.

Asian dust events observed in South Korea were 12.3 days in 2010 that are higher than the annual mean events of 9.6 days for the recent 10 year period (2000-2009). Of which 0.5, 5.0,

Table 1. Quantitative performance statistics for near surface aerosol (PM_{10}) concentration simulations with AMS in South Korea. Mean (o) and Mean (m) represent the observed and modeled mean concentration (μg m^{-3}), respectively; SD (o) and SD (m) the ovserved and modeled standard devitaion (μg m^{-3}), respectiviely; BIAS the mean BIAS (μg m^{-3}); MNB the mean normalized BIAS (%); CORRCOEF the correlation coefficeient; RMSE the root mean square error (μg m^{-3}); NMSE the normalized mean square error (%); FAC2 the fraction of simulations within a factor of 2 of observations.

Month	Mean (o) (μg m^{-3})	Mean (m) (μg m^{-3})	SD (o) (μg m^{-3})	SD (m) (μg m^{-3})	BIAS (μg m^{-3})	MNB (%)	CORR COEF	RMSE (μg m^{-3})	NMSE (%)	FAC2 (%)
1	41.5	44.8	25.0	36.2	3.1	7	0.62	11.6	7.2	71
2	35.7	39.6	22.3	34.0	3.0	8	0.60	10.4	7.8	67
3	54.5	58.1	67.0	66.4	3.6	7	0.65	3.6	0.4	63
4	39.6	53.6	22.7	50.2	14.5	36	0.48	30.6	44	65
5	45.5	50.1	34.7	45.7	4.9	11	0.72	12.0	6.3	64
6	28.9	25.3	21.9	15.6	-3.5	-12	0.44	6.9	6.5	58
7	23.9	15.8	17.2	12.2	-8.0	-34	0.55	9.4	23.5	57
8	25.9	25.3	20.3	19.9	-0.6	-2	0.50	0.7	0.1	47
9	24.9	21.1	18.1	16.4	-3.8	-15	0.50	4.1	3.2	55
10	34.8	28.0	18.8	20.5	-6.8	-19	0.51	7.0	5.0	62
11	62.8	58.2	61.4	58.4	-4.6	-7	0.53	5.5	0.8	68
12	53.6	57.1	44.6	51.7	3.8	7	0.65	8.0	2.1	67
Annual mean	39.3	39.7	21.2	35.6	0.5	0.3	0.56	9.2	5.5	62

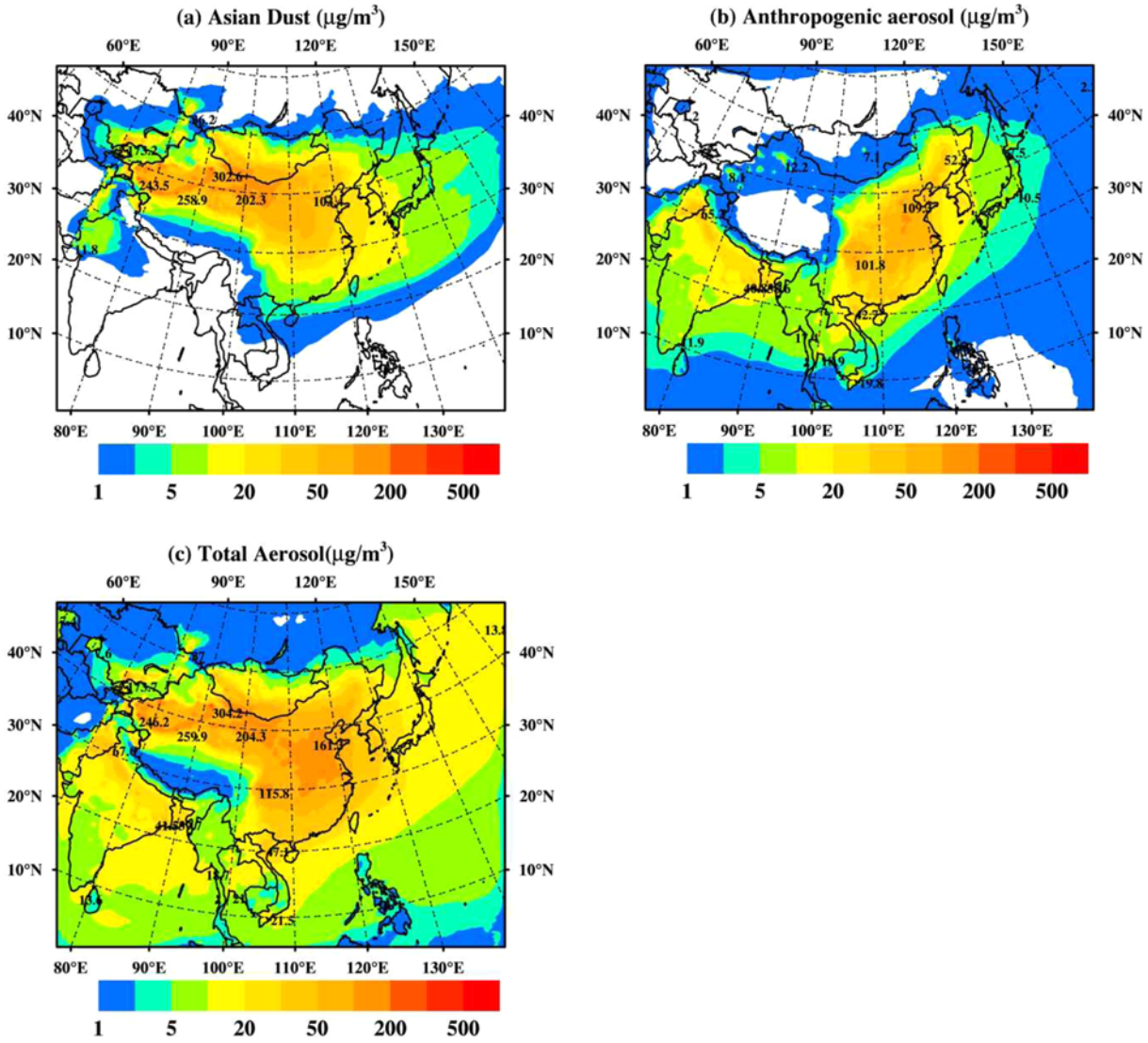

Fig. 6. Spatial distributions of annual mean surface PM_{10} concentration ($\mu g\ m^{-3}$) of (a) Asian dust aerosol, (b) anthropogenic aerosols (SIA, SOA, BC, OC, anthropogenic PM_{10}) and (c) total aerosol simulated by AMS for the year 2010. Numbers indicate the local maximum values.

0.9, 0.8, 2.5 and 2.6 days were, respectively reported in January, March, April, May, November and December with the maximum PM_{10} concentration of 2,700 $\mu g\ m^{-3}$ on 12-21 March and 1,660 $\mu g\ m^{-3}$ on 11-13 November 2010 at some monitoring sites in South Korea.

b. Spatial distributions of annual mean PM_{10} concentrations

Figure 6 shows the model simulated annual mean surface mean aerosol concentration (PM_{10}) averaged for the whole year of 2010 with the inclusion of emissions of South Korea in Fig. 3. The Asian dust (AD) aerosol (Fig. 6a) originated from the AD source region (Fig. 1) affects far downwind region of the Northwestern Pacific Ocean. The annual mean AD aerosol concentration exceeding 10 $\mu g\ m^{-3}$ covers over eastern China, the north of the Tibetan Plateau, the most parts of Mongolia, Korea peninsula, the Yellow Sea and the East China Sea with a maximum concentration of more than 300 $\mu g\ m^{-3}$ at the northeastern Taklimakan desert. On the other hand the annual mean surface anthropogenic aerosol (AA) concentrations (Fig. 6b) including SIA, OC, BC SOA and emitted PM_{10} that are originated from pollutants emissions affect almost all over the Asian region. The annual mean AA concentration exceeding 10 $\mu g\ m^{-3}$ covers all over the eastern and southern parts of China, Korean peninsula and northern India where pollutants emissions are large (Fig. 2), with a maximum concentration exceeding 110 $\mu g\ m^{-3}$ near Beijing.

Therefore, the annual mean surface total aerosol concentration (AD + AA) affects all Asian regions (Fig. 6c). The annual mean high surface aerosol concentration exceeding 50 $\mu g\ m^{-3}$ extends eastward from the Taklimakan desert region to northeast China with the maximum concentration of more than

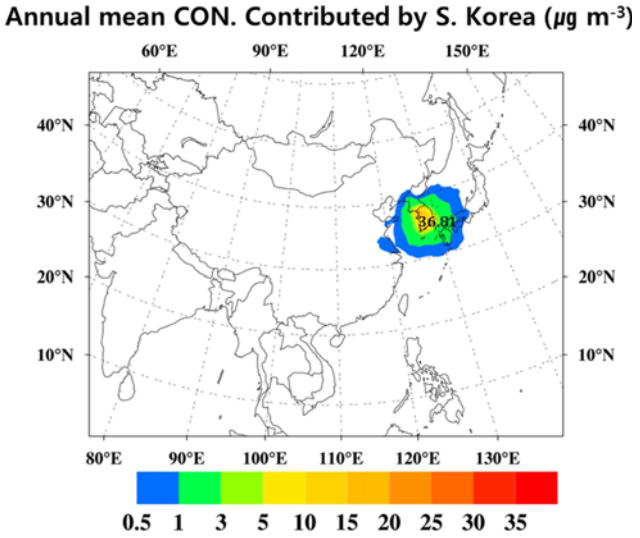

Fig. 7. The spatial distribution of the annual mean PM_{10} concentration ($\mu g\ m^{-3}$) contributed by the pollutant emission in South Korea.

304 $\mu g\ m^{-3}$ at the eastern part of the Taklimakan desert area mainly contributed by the AD aerosol (Fig. 6a). Another annual mean high aerosol concentrations exceeding 50 $\mu g\ m^{-3}$ occur in the most parts of eastern China and northern India in the high pollutant emission region (Fig. 2) with a maximum concentration of more than 160 $\mu g\ m^{-3}$ near Beijing. These are mainly contributed by AAs.

The impact of the pollutant emission from South Korea (Fig. 3) on the distribution of aerosol concentrations in Asia is obtained by subtracting the model results simulated without the pollutant emission from South Korea (Fig. 3) from those with the pollutant emissions in the whole model domain (Figs. 2 and 3). Figure 7 shows the spatial distribution of the annual mean surface aerosol (PM_{10}) concentration due to the pollutant emission from South Korea (Fig. 3). The impact of the pollutant emission from South Korea on the Spatial distribution of aerosol concentration is limited within the neighboring regions of South Korea including the Yellow Sea, the East Sea of Korea, the southern parts of Japan and the northern part of the East China Sea with the maximum annual mean concentration of 36.8 $\mu g\ m^{-3}$ near Seoul in Korea. Note that the aerosol in Fig. 7 is contributed by AA only since there is no AD source in South Korea.

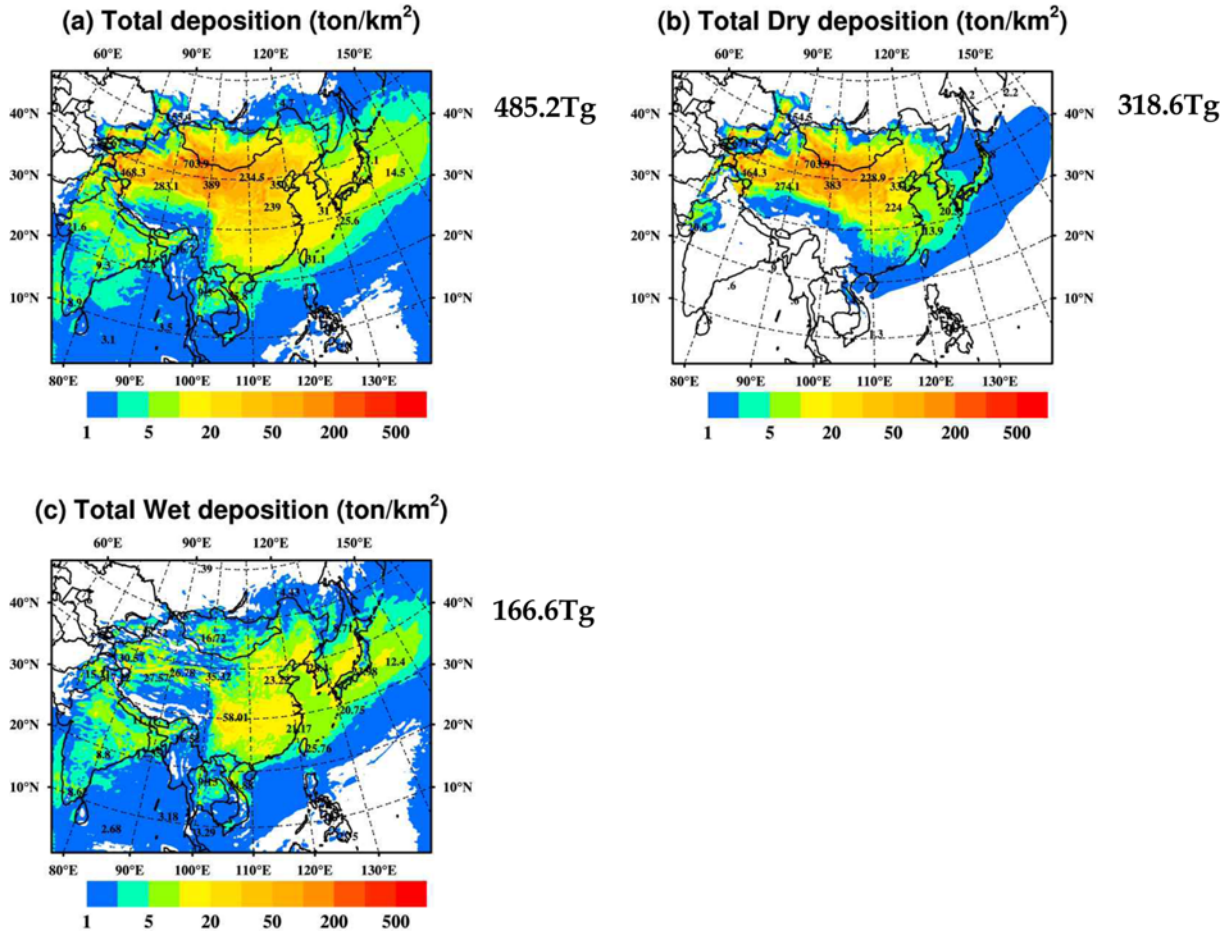

Fig. 8. Spatial distribution of the annual (a) total aerosol deposition (dry + wet; ton km^{-2}), (b) total dry deposition (ton km^{-2}) and (c) total wet deposition (ton km^{-2}). The annual total depositions in the model domain are indicated as numbers (Tg).

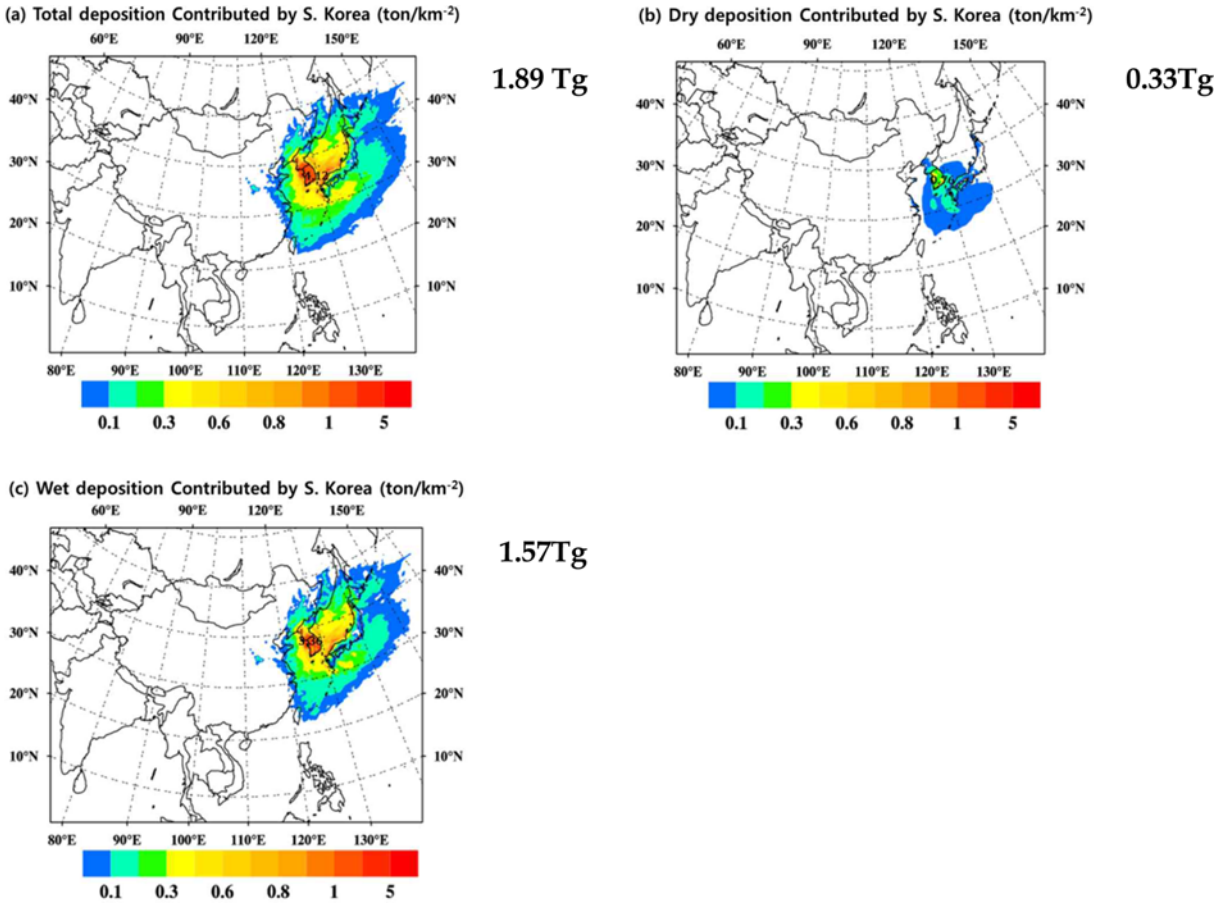

Fig. 9. The same as in Fig. 8 except for the contribution due to the pollutant emission from South Korea.

c. Spatial distributions of annual total depositions of aerosols (AD + AA)

The model simulated annual total depositions of the AD aerosol and AA for 2010 are reported in Park et al. (2014) and Park (2015) so that for our convenience the annual total aerosol deposition (AA + AD) is presented in Fig. 8.

Figure 8 shows annual total aerosol deposition of all kinds of aerosols (AA + AD) in the Asian domain. The spatial distribution pattern follows that of the annual mean surface concentration (Fig. 6c). The high aerosol deposition of more than 300 ton km^{-2} yr^{-1} (Fig. 8a) occurs in northern China and southern Mongolia in the AD source region (Fig. 1) whose distribution pattern is quite similar to that of the annual mean AD aerosol concentration (Fig. 6a).

The annual total aerosol deposition in the whole model domain is 485.2 Tg, of which 66% (318.6 Tg) is contributed by the dry deposition (Fig. 8b) and 34% (166.6 Tg) by the wet deposition (Fig. 8c).

The spatial distribution of the dry deposition (Fig. 8b) is similar to that of the annual mean AD concentration (Fig. 6a) whereas that of wet deposition (Fig. 8c) is similar to that of the annual mean AA concentration (Fig. 6b), suggesting the importance of AA for the wet deposition and the AD aerosol for the dry deposition.

The impact of the pollutant emission from South Korea on the annual total aerosol deposition in Asia is given in Fig. 9. This is obtained from the difference of the model results simulated with and without the pollutant emission from South Korea. The spatial distribution pattern of the annual total aerosol deposition follows that of the annual mean aerosol concentration (Fig. 7) with a maximum total deposition of 4.1 ton km^{-2} in South Korea. However, the area affected by the aerosol deposition (Fig. 9a) is wider than that by the annual mean concentration (Fig. 7) extending further northeastward from Taiwan to the Northwest Pacific Ocean through South Korea. The annual total deposition due to the pollutant emission in South Korea is about 1.89 Tg (Fig. 9a), of which 0.33 Tg (17% of the total deposition) is contributed by the dry deposition process (Fig. 9b) and 1.57 Tg (83% of the total deposition) by the wet deposition process (Fig. 9c), suggesting the importance of the wet deposition process for the removal of AA aerosol from the atmosphere.

The contribution due to the pollutant emission from South Korea to the annual total deposition in Asia (485.2 Tg) is about 0.4% through the dry deposition of 0.07% and the wet deposition of 0.33%. The contribution of South Korea to the total deposition in Asia is of no significance.

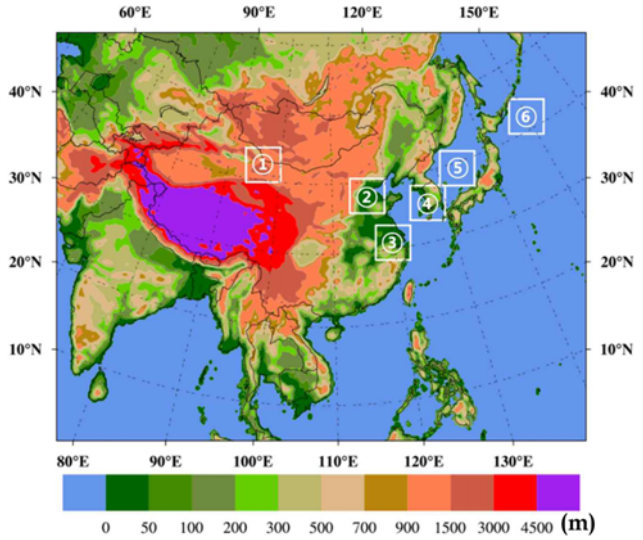

Fig. 10. The selected regions for the estimations of surface aerosol (AA and AD) concentration and total aerosol deposition. R1 represents the AD source region, R2 and R3 the high air pollutant emission region in China including Beijing and Shanghai, respectively, R4 South Korea, R5 the East Sea and R6 the Northwest Pacific Ocean. The topographical height is indicated by color.

d. Spatial variations of PM_{10} concentrations and deposition in Asia

To understand spatial variations of aerosol concentration and deposition, 6 regions (R1, R2, R3, R4, R5 and R6) are chosen in the Asian domain (Fig. 10). The region R1 is located in AD source region including parts of northwestern Gansu, northeastern Xinjang, southwestern Mongol and western tip of Inner Mongolia, the region R2 in the high air pollutant emission region including Beijing, the region R3 including Shanghai, the region R4 over South Korea, the region R5 over the East Sea and the region R6 over the Northwest Pacific Ocean. R2 and R3 are located in the high pollutant emission regions in China (Fig. 2) whereas R4, 5 and 6 are located in the downwind region of AD source and high pollutant emission regions (Figs. 1 and 2).

The annual mean aerosol concentration in each region with the indication of the contribution due to the pollutant emission from South Korea is given in Fig. 11. The annual mean aerosol concentration in AD source region of R1 is 98.5 μg m^{-3}, of which almost all of it is contributed by AD aerosol. The annual mean AD (AD + AA) aerosol concentration tends to decrease away from the source region to 48 (112) in R2, 24 (74) in R3, 17.7 (35) in R4, 9.1 (17) in R5 and 3.6 (6.5) μg m^{-3} in R6. However, in the high pollutant emission regions of R2 and R3 the contribution of AA is greater than that of AD, so that the annual mean aerosol concentration in R2 is higher than that in R1. In the further downwind regions of R4, R5 and R6, the contribution of AA to the annual mean total aerosol concentration is almost the same as that of AD, suggesting the importance of the mixture of AA and AD aerosols. The

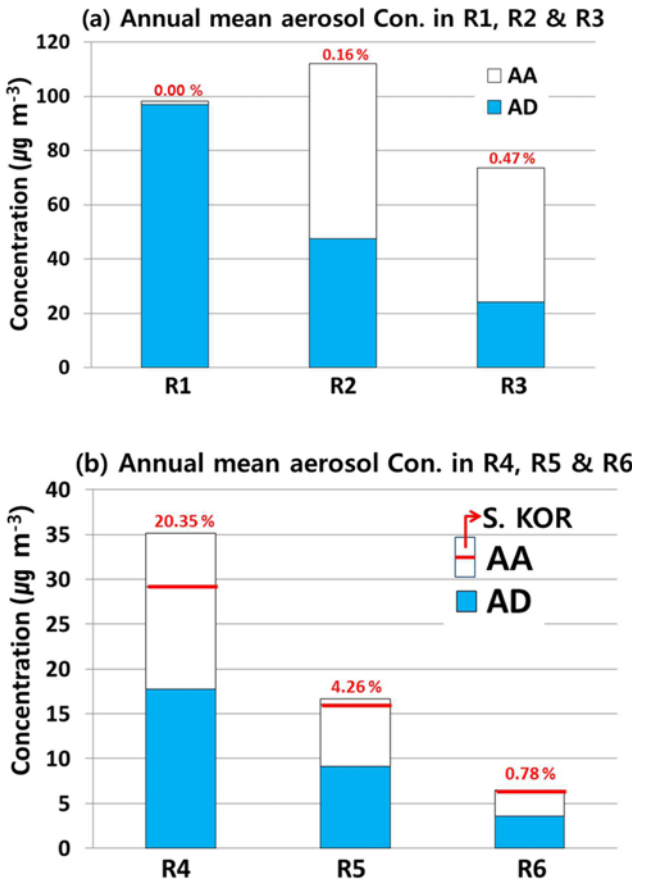

Fig. 11. Annual mean aerosol concentration (μg m^{-3}) contributed by AA (□) and AD (■) aerosol in (a) R1, R2 and R3 and (b) R4, R5 and R6. The percent contribution due to the pollutant emission from South Korea to the annual mean concentration in each region is indicated. The concentration above the red bar indicates the contribution due to the South Korea emission.

contribution due to the pollutant emission from South Korea to the annual mean aerosol concentration is negligible in the upwind regions of R1, R2 and R3. However it affects far downwind region of the Northwest Pacific Ocean. The contribution of the pollutant emission from South Korea to the annual mean aerosol concentration in each region is 20.4% in R4, 4.3% in R5 and 0.8% in R6, suggesting more than 79% of the annual mean aerosol concentration in South Korea (35.6 μg m^{-3}) being affected by aerosols produced from other regions.

e. Spatial variations of aerosol depositions

Figure 12 shows the annual total aerosol deposition in each region. The annual total maximum deposition of more than 115 ton km^{-2} occurs in R1 (AD source region) that is mainly contributed by the dry deposition process. Away from the AD source region (R1) the annual total aerosol deposition decreases from 41 ton km^{-2} in R2 to 6 ton km^{-2} in R6 over the Northwest Pacific Ocean. But the contribution of wet deposition increases from 20% in R2 to 82% in R6 of their respective

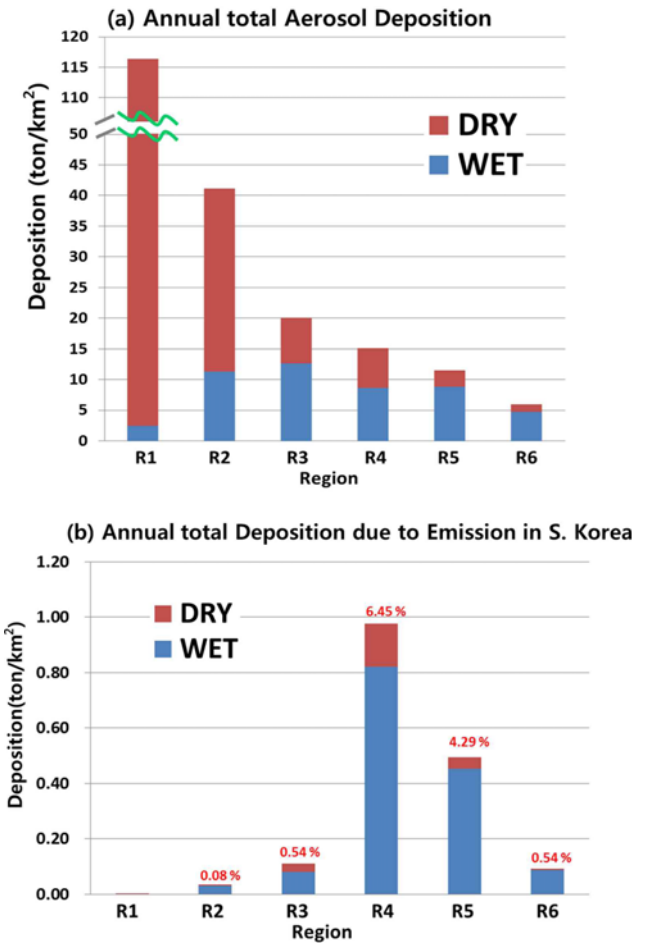

Fig. 12. (a) The annual total aerosol deposition (ton km^{-2}; dry; wet) and (b) the contribution due to the pollutant emission from South Korea with the indication of the percent contribution (%) to the annual total aerosol deposition in each region (R1-R6).

annual total deposition (Fig. 12a).

The contribution due to the pollutant emission from South Korea to the annual total deposition in each region decreases away from South Korea with a maximum of 0.96 ton km^{-2} (6.5% of annual total deposition) in R4 (Fig. 12b) to 0.02 ton km^{-2} (0.08% of the annual total) in R2 and 0.12 ton km^{-2} (0.5% of the annual total) in R3 in the upwind region whereas it becomes 0.5 ton km^{-2} (4.3% of the annual total) in R5 and 0.1 ton km^{-2} (0.5% of the annual total) in R6 in the downwind region, suggesting the contribution of the pollutant emission from South Korea being small especially in the upstream regions. It is interesting to note that the fractional contribution due to the pollutant emission from South Korea to the annual mean aerosol concentration of South Korea (20.4% in Fig. 11b) is as large as 3 times that to the annual total aerosol deposition in South Korea (6.5% in Fig. 12b). This implies that the local pollutant emission contributes more to the increase of the aerosol concentration than that of the deposition in the source region.

The above results clearly indicate that the reduction of the pollutant emission of other countries especially in China is prerequisite to reduce the aerosol concentration and deposition over South Korea.

4. Conclusions

Aerosol Modeling System (AMS) that is composed of the Asian Dust Aerosol model2 (ADAM2) for the Asian dust (AD) aerosol modeling and the Community Multi-scale Air Quality (CMAQ) Version 4.7.1 modeling system for the anthropogenic aerosol (AA) modeling has been employed to document a year-long spatial distributions of the annual mean PM_{10} concentration and total depositions of the AD aerosol and AAs, and with the relative contribution due to the pollutant emission from South Korea in the Asian domain.

AMS is found to simulate quite reasonably the monitored annual mean aerosol concentrations in South Korea with a BIAS of 0.5 μg m^{-3} and a mean normalized BIAS of 0.3%.

It is found that the annual mean surface concentration of the AD aerosol exceeding 10 μg m^{-3} extends eastward from northwestern China in the Asian dust source region to the Northwest Pacific Ocean with the annual mean maximum concentration of more than 300 μg m^{-3} in the northeastern part of the Takhlimakan desert. Whereas that of AA exceeding 10 μg m^{-3} covers over the eastern and southern parts of China, northern India and the Korean peninsula with the annual mean maximum concentration of 110 μg m^{-3} over the Shandong province where the pollutant emissions are high.

It is found that the annual total aerosol deposition in the Asian domain is 485 Tg, of which 319 Tg (66%) is found to be contributed by the dry deposition and 167 Tg (34%) by the wet deposition. This suggests that the total aerosol deposition can affect significantly both the terrestrial and marine eco-systems in the Asian region.

The spatial variations of the annual mean aerosol concentration (PM_{10}) in several regions including the Asian dust source region (R1), high pollutant emission regions in China (R2 and R3) and the downwind regions (R4, R5 and R6) clearly indicate that the AD aerosol is predominated in the AD source region (R1) with the annual mean concentration of 98.5 μg m^{-3}, whereas a mixture of AA and the AD aerosols is dominated in the high pollutant emission region (R2 and R3) and the downwind region (R4, R5 and R6) with the highest annual mean aerosol concentration of 112 μg m^{-3} in R2. The contribution due to the pollutant emission from South Korea to the annual mean concentration is negligible in the upwind regions of R1, R2 and R3 but that is 20.4%, 4.3% and 0.8% of their respective annual mean concentrations in R4, R5 and R6, respectively, suggesting more than 79% of the annual mean aerosol concentration in South Korea (R4) being contributed by sources other than South Korea.

The annual total aerosol deposition is found to decrease away from the AD source region (R1) from 116.4 ton km^{-2} in R1, to 41.2 ton km^{-2} in R2, 20.3 ton km^{-2} in R3, 16.1 ton km^{-2} in R4, 12.0 ton km^{-2} in R5, and 6.1 ton km^{-2} in R6. The con-

tribution due to the pollutant emission from South Korea to annual total aerosol deposition is found to be 0.03 ton km^{-2} in R2, 0.11 ton km^{-2} in R3, 0.97 ton km^{-2} in R4, 0.49 ton km^{-2} in R5 and 0.09 ton km^{-2} in R6 mainly through the wet deposition process.

The annual total aerosol deposition in the whole Asian domain due to the pollutant emission from South Korea is about 1.9 Tg (0.3 Tg by dry deposition and 1.6 Tg by wet deposition) that is only 0.4% of the annual total aerosol deposition in Asia (485.2 Tg), suggesting the contribution of the pollutant emission from South Korea to the annual mean aerosol concentration and deposition in Asia being of no significance.

This study mainly pertains to the documentation of the spatial distributions of concentrations and depositions of the AD aerosol and AAs with the contribution due to the pollutant emission from South Korea in the Asian domain for the year 2010. However, the impact assessment of these aerosols on environment and eco-system, and the mitigation measures for the pollutant emissions in the Asian domain require model simulated data for several years with more accurate emission inventory data since the year by year dust occurrence frequencies and the meteorological conditions in this region are changing. The presently developed methodology will be implemented to simulate the aerosol concentrations and depositions in this region for several years.

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