Spatial distributions of aerosol concentrations and depositions in Asia during the year 2010

SOON-UNG PARK
Center for Atmospheric and Environmental Modeling
24 Digital-ro 27-gil Guro-gu, Seoul
SOUTH KOREA
supark@snu.ac.kr

Abstract

Aerosol Modeling System (AMS) that is consisted of the Asian Dust Aerosol Model2 (ADAM2) and the Community Multi-scale Air Quality (CMAQ) modeling system has been employed to document the spatial distributions of the annual averaged both the Asian dust (AD) aerosol and the anthropogenic aerosol (AA) concentrations and their total depositions in several chosen regions and the Asian region for the year 2010. It is found that the annual mean surface aerosol (PM$_{10}$) concentrations in the Asian region affect in a wide region as a complex mixture of AA and AD aerosols; they are predominated by the AD aerosol in the AD source region of northern China and Mongolia with a maximum annual mean concentration exceeding 300 µg m$^{-3}$;AAs are predominated in the high pollutant emission regions of southern and eastern China and northern India with a maximum concentration exceeding 110 µg m$^{-3}$; while the mixture of AA and AD aerosols is dominated in the downwind regions extending from the Yellow Sea to the Northwest Pacific Ocean. It is also found that the annual total deposition of aerosols in the model domain is found to be 485.2 Tg (371. 8 Tg by AD aerosol and 113.4 Tg by AA), of which 66 % (318.6 Tg) is contributed by the dry deposition (305.3 Tg by AD aerosol and 13.3 Tg by AA) and 34 % (166.6 Tg) by the wet deposition (66.3 Tg by AD aerosol and 100.1 Tg by AA), suggesting about 77 % of the annual total deposition being contributed by the AD aerosol mainly through the dry deposition process and 23 % of it by AA through the wet deposition process.

Key-words: ADAM2, Aerosol Modeling System (AMS), Anthropogenic aerosol, Asian Dust aerosol, CMAQ, Concentration, Deposition

1. Introduction

Atmospheric aerosols can affect the quality of our lives significantly because of its potential impacts on human health and the environment. The sub-micrometer size of aerosols can be inhaled and thus may pose certain health hazards [1-7], resulting in an increase in mortality[8-10] and in respiratory [11] and cardiovascular diseases [12-13]. Because aerosols also scatter light, they strongly influence the radiative budget of the Earth-atmosphere system; they also reduce visibility and diminish the aesthetic scenery [14-23]. Depositions of aerosols can affect significantly the terrestrial and marine eco-systems[24].

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 [25-30]. 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 [31-34]. Therefore the atmospheric aerosols in this region are the complex mixture of various aerosols including Asian dust and anthropogenic aerosols (Secondary inorganic aerosol, Secondary organic aerosol, Black carbon, Organic carbon, Water droplet and emitted particulate matter) [35].

Recently [34] 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 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 [36] and in January 2013 [37] in East Asia and found to simulate successfully these events.

Impact assessments of aerosols on the health, environment, eco-systems and climate variation...
require temporal and spatial distributions of aerosols with chemical compositions for a long term. However, long-term statistical data of aerosols are not usually available. The present study will provide a year-long data set of aerosols to make it possible to assess the effects of aerosols on health and environment.

The purpose of this study is to examine the spatial distributions of Asian dust and anthropogenic aerosols including Secondary Inorganic aerosol (SIA), Black Carbon (BC), Organic Carbon (OC), Secondary organic aerosol (SOA) and anthropogenic PM$_{10}$ concentrations and their depositions simulated by the Aerosol Modeling System (AMS) in the Asian domain for the year 2010.

2. Model descriptions

2.1. Meteorological model

The meteorological model used in this study is the fifth generation meso-scale model of non-hydrostatic version (MM5; Pennsylvania State University / National Center for Atmospheric Research) defined in the x, y and $\sigma$ coordinate [38-39]. 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 on a 1.0 × 1.0 degree grid are used for the initial and lateral boundary conditions for the model.

2.2. Aerosol Modeling System (AMS)

The Aerosol Modeling System (AMS) is consisted of the Asian Dust Aerosol Model2 (ADAM2;[40]) and the Community Multiscale Air Quality (CMAQ) version 4.7.1 modeling system with emission data of pollutants (SO$_2$, NOX, VOC, CO, NH$_3$, BC, OC and PM$_{10}$) in the model domain.

2.2.1. 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 lognormal distributions in the source regions, based on the parent soil particle-size distributions with the used of the concept of the minimally and fully dispersed particle-size distribution [29, 41-43]. It has 11-size of bins with near the same logarithm interval for particles of 0.15-35 $\mu$m in radius [28-29]. 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 is given in [41].

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.

2.2.2. 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 modeling system that simulates airborne pollutants, ozone concentration, particulate matters, visibility, and acidic and nutrient pollutant species throughout the troposphere [44]. The aerosol component of the CMAQ model has the particle size distribution as the superposition of three lognormal sub-distributions, called modes. Fine particles with diameters less than 2.5 $\mu$m (PM$_{2.5}$) are represented by two sub-distributions
called the Aitken and accumulation modes. The Aitken mode includes particles with diameters up to approximately 0.1 \( \mu m \) for the mass distribution and the accumulation mode covers the mass distribution in the range from 0.1 to 2.5 \( \mu m \). The coarse mode covers the mass distribution in the range from 2.5 to 10 \( \mu m \). The model includes the processes of coagulation, particle growth by the addition of mass and new particle formation [45].

2.2.3. 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 [46]. More than 60% of the total Asian anthropogenic emissions are contributed by China.

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 re-gridded in a 27 × 27 km\(^2\) grid scheme for the simulation of aerosols in the model.

3. Results of the model simulation
3.1. 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).

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\(^2\)).

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 Korean domain (1 grid: 27× 27 km\(^2\)).

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 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.
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 09:00 LST 8 to 09:00 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.

Fig. 5. Temporal variations of the observed ( ) and modeled ( ) monthly mean PM$_{10}$ concentrations (µg m$^{-3}$) with the indication of +/- one standard deviation (vertical line) averaged over South Korea with the use of hourly monitored and simulated data at 28 monitoring sites.

3.2. Spatial distributions of annual mean PM$_{10}$ concentrations

Figure 6 shows the model simulated surface mean aerosol concentration (PM$_{10}$) averaged for the whole year of 2010. The Asian dust (AD) aerosol (Fig. 6a) originated in the AD source region (Fig. 1) affects far downwind region of the Northwestern Pacific Ocean. The annual mean AD aerosol concentration exceeding 10 µg m$^{-3}$ covers all over the eastern and southern parts of China, Korean peninsula, the Yellow Sea and the East China Sea with a maximum concentration of more than 300 µg 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 µg 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 µg m$^{-3}$ in 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 50µg m$^{-3}$ extends...
eastward from the Taklimakan desert region to northeast China with the maximum concentration of more than 304 \( \mu g \) m\(^{-3}\) at the eastern part of the Taklimakan desert area. This is mainly contributed by the AD aerosol (Fig. 7a). 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.

3.3. Spatial distributions of annual total depositions of AD and AA

Figure 7 shows the spatial distributions of annual total depositions of the AD aerosol for 2010. The spatial distribution pattern of the annual total deposition (dry + wet) (Fig. 7a) just follows that of the annual mean surface AD concentration (Fig. 6a). The zone of the maximum deposition extends downwind ward from the AD source region (Fig. 1) to the northwest Pacific Ocean with the maximum annual total deposition of more than 703 t km\(^{-2}\) at the northeastern Taklimakan desert. The total deposition of AD aerosol over AD source region and the land region is mainly contributed by the dry deposition process (Fig. 7b) whereas over the ocean the wet deposition (Fig 7c) is largely contributed to the total deposition. The annual total deposition of AD aerosol originated from the AD source region exceeds 10t km\(^{-2}\) over the northwestern Pacific Ocean that may affect marine ecology in this region. The annual total dust deposition in the model domain is about 371.8 Tg (305.3 Tg by dry deposition and 66.5 Tg by wet deposition) which is slightly lower than that estimated by [47] in 2007 (821.0 Tg) but slightly higher than that estimated by IPCC (241.0 Tg), suggesting a high variability dust occurrence frequency in each year.

Figure 8 shows the spatial distribution of the annual total AA deposition. The spatial distribution pattern of the total deposition (wet + dry) of AA (Fig. 8a) is quite similar to that of the annual mean concentration of AA (Fig. 6b) with the maximum deposition of 45.0 t km\(^{-2}\) in the Sichuan province. Most of the annual total deposition of AA is mainly contributed by the wet deposition (Fig. 8c) rather than the dry deposition (Fig. 8b). The dry deposition of AA is one order magnitude smaller than that of the wet deposition. The annual total deposition of AA in the whole model domain is about 113.4 Tg, which is one-third of AD aerosol, of which 88 \% (100.1 Tg) is contributed by wet deposition mainly in the high pollutants emission region (Figs. 2 and 8c) and the rest of 12 \% (13.3 Tg) is contributed by the dry deposition (Fig. 8b).

Figure 9 shows annual total aerosol deposition (AD + AA) of all kinds of aerosols in the Asian domain. High aerosol deposition of more than 300 t km\(^{-2}\) yr\(^{-1}\) (Fig. 9a) occurs in northern China and...
Mongolia mainly due to AD. The annual total aerosol deposition in the whole model domain is 485.2 Tg, of which 77% (371.8 Tg) is contributed by the AD aerosol and 23% (113.4 Tg) is contributed by AA. This total deposition is largely contributed by dry deposition (66%; 3% by AA and 63% by AD aerosol) in the AD source region (Fig. 7b).

It is quite clear that the dry deposition process is more effective for AD aerosol to remove the aerosol from the atmosphere while the wet deposition process is more effective for AA. This may be attributed to the difference of the particle-size distributions between AD and AA. The former is relatively larger than the latter. High aerosol deposition over southern and eastern China, over the Yellow Sea, the East Sea of Korea, the South China Sea and the eastern part of Japan are largely contributed by AAs that are mainly contributed by the wet deposition (Fig. 8c).

3.4. Regional variations of PM$_{10}$ concentrations in Asia

AMS is found to simulate quite reasonably the monitored aerosol concentrations in Korea (Figs. 4 and 5) so that the model simulated results can be used to document the spatial and temporal distributions of concentrations and depositions of the AD aerosol and AA in the whole Asian domain.

Fig.10. Regions that are estimated 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.

To understand regional variations of aerosol concentration and deposition, six regions (R1, R2, R3, R4, R5 and R6) are chosen (Fig. 10). The region R1 is located in AD source region including parts of northwestern Gansu, northeastern Xinjiang, southwestern Mongolia 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 whereas R4,5 and 6 are located in the downwind region of AD source and high pollutant emission regions.

The annual mean aerosol concentration in each region is given in Fig. 11. The annual mean aerosol concentration on 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 reduce away from
the source region to be 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 aerosol concentration is almost the same as that of AD, suggesting the importance of the mixture of AA and AD aerosols.

4. Conclusions

Aerosol Modeling System (AMS) that is consisted of the Asian Dust Aerosol model2 (ADAM2) for the Asian dust (AD) aerosol modeling and the Community Multi-scale Air Quality (CMAQ) modeling system for the anthropogenic aerosol (AA) modeling has been employed to document a year-long spatial distributions of the AD aerosol and the AAs in the Asian domain. The spatial distributions of annual mean surface concentrations, annual total dry and wet depositions of both the AD aerosol and AA have been documented for the first time in the whole Asian domain.

AMS is found to simulate quite reasonably the monitored aerosol concentrations in Korea so that the model simulated results can be used to document the spatial and temporal distributions of concentrations and depositions of the AD aerosol and the AA in the whole Asian domain.

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 of the Taklimakan desert to the Northwest Pacific Ocean with maximum concentration of more than 300 µg m$^{-3}$ at the northeastern part of the Taklimakan 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 maximum concentration of 110 µg m$^{-3}$ over the Shandong province where the pollutants emissions are high.

Consequently the annual mean surface total aerosol (AD + AA) concentration exceeding 10 µg m$^{-3}$ extends further downwind region from northwestern China to the Northwest Pacific Ocean. Another annual mean high aerosol concentration occurs in northern India and over the Bay of Bengal caused by AA.
It is found that the annual total deposition of the AD aerosol in the whole Asian domain (model domain) is about 371.8 Tg, of which 82% (305.3 Tg) is contributed by the dry deposition mainly in the Asian dust source region and 18% (66.5 Tg) is contributed by the wet deposition mainly over oceans, whereas the annual total deposition of AA in the whole model domain is 113.4 Tg, of which 88% (100.1 Tg) is contributed by the wet deposition largely over the high pollutant emission regions. Consequently, the annual total aerosol deposition in the Asian domain is found to be 485.2 Tg (371.8 Tg by the AD aerosol and 113.4 Tg by AA), of which 318.6 Tg (66%) is found to be contributed by the dry deposition (305.3 Tg by the AD aerosol and 13.3 Tg by AA) and 166.6 Tg (34%) by the wet deposition (100.1 Tg by AA and 66.3 Tg by Asian dust aerosol). This suggests that the total aerosol deposition (the AD aerosol and AA) can affect significantly both the terrestrial and marine eco-systems in the Asian region.

The regional variations of 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 of South Korea (R4), the East Sea of Korea (R5) and the Northwestern Pacific Ocean (R6) clearly indicate that most of aerosols in R1 are found to be composed of the AD aerosol.

In the high anthropogenic air pollutant emission region in China of R2 and R3 the aerosols are found to be composed a mixture of AA and the AD aerosols.

In the further downwind regions of R4, R5 and R6, annual mean total aerosol concentration is found to decreases away from the sources of AD and AA from the maximum of 35.1 $\mu$g m$^{-3}$ in R4 to 6.5 $\mu$g m$^{-3}$ in R6.

The annual total aerosol deposition is found to decrease away from the AD source region (R1); from 116.4 t km$^{-2}$ (100% AD) in R1 (AD source region), 41.2 t km$^{-2}$ (78% AD and 12% AA) in R2 (Beijing), 20.3 t km$^{-2}$ (48% AD and 52% AA) in R3 (Shanghai), 16.1 t km$^{-2}$ (67% AD and 33% AA) in R4 (South Korea), 12.0 t km$^{-2}$ (61% AD and 39% AA) in R5 (East Sea), to 6.1 t km$^{-2}$ (61% AD and 39% AA) in R6 (Northwest Pacific Ocean). The large portion of deposition of the AD aerosol is found to be contributed by the dry deposition process while that of AA is by the wet deposition process.

Acknowledgements

This research is supported by Korea Meteorological Administration through the research project of the development of the aerosol prediction model.

References


