Performance Tests of the Asian Dust Aerosol Model 2 (ADAM 2)

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Abstract: The Asian Dust Aerosol Model 2 (ADAM2) was developed to enhance the ability to deliver timely and quality sand and dust storm forecasts to all Asian countries that might be affected by such storms. The ADAM2 model, modified from the operational ADAM/ADAM1 model used by the Korea Meteorological Administration, utilizes statistically-derived threshold wind speeds with the use of 3 hourly reporting WMO surface data in the whole Asian domain (60-160E, 10-60N) for the period of 1998 to 2006. This also uses the parameterized emission reduction factors due to the vegetation in the Asian dust source region with the use of a Normalized Difference Vegetation Index (NDVI) obtained from Spot/Vegetation product of Maximum Value Composite Syntheses for the same period. Both the threshold wind speeds and the emission reduction factors due to the vegetation vary with time and surface soil types (Gobi, Sand, Loess, and mixed soil). A performance test of the ADAM2 model was conducted with observed PM_{10} concentrations at some monitoring sites in the source region and the downstream region of Korea for the whole months of May and December in 2007. It was found that the ADAM2 model was able to simulate quite well most of Asian dust-storm occurrences in the source region and dust events observed in Korea. The model simulates quite well the starting and ending times of the dust storms in the source region within 10 % margin of error with the observed surface PM_{10} concentration. In the downstream region of Korea, the starting and ending times of dust events were well-simulated; however, the surface PM_{10} concentration was slightly overestimated for some dust events. Nevertheless, there is great potential for the ADAM2 model to be used as an operational Asian dust forecast model for Asia.

Keywords: ADAM, Asian dust source region, Emission reduction factor, NDVI, Threshold wind speed.

1. Introduction

Asian dusts, called Hwangsa in Korean and Kosa in Japanese, are typical examples of mineral aerosol storms that frequently originate in the Gobi desert, Sand desert, the Loess plateau and barren mixed soil area in northern China and Mongolia [1-3]. They occur all year round with maximum frequency in spring [4]. These storms tend to cause major aerosol events well beyond the Asian continent [5] and often have catastrophic consequences to humans and their environment such as temporary closing of airports and schools [3,6], not only in the source regions but in the far downstream regions.

In 2002, the Asian Dust Aerosol Model (ADAM) was developed to forecast the Asian dust events observed in Korea [2,3,7] and was used successfully to forecast severe dust events observed in Korea during 21-22 March and 7-9 April 2002 [2,3]. Thereafter, this model has been modified to the ADAM1 model [6] with the use of monitoring tower data located in the source region in northern China. The modification has been done by comparing modelled and monitored meteorological parameters including relative humidity, soil surface temperature, surface friction velocity and surface vegetation conditions. This model has been used successfully since 2003 to forecast Asian dust events observed in Korea [6].

Both ADAM and ADAM1 use the total dust emission flux parameterized for Saharan dust outbreaks [8,9] where sandy soil predominates. However, the Asian dust source regions are composed of Gobi, Sand, Loess and mixed soils [1-3,7] so that a parameterization of the total dust emission flux from different surface soil types in different source regions [10] has been developed using saltation fluxes [11] with the observed clay content in each soil type [12]. The newly parameterized total dust emission flux has been employed for the simulation of a dust event observed in Korea during 20-22 April 2005. The result indicated that the modified model was capable of simulating the starting and ending times of the dust event and the maximum dust concentration slightly better than the ADAM1 model in Korea.

ADAM1, as an operational model to forecast dust events has been used by the Korea Meteorological Administration (KMA) mainly to forecast dust events over the Korean peninsula during the spring season, when the frequency of dust events is the highest. Therefore, the model uses a rather small domain (20-60N and 95-150E) (Fig. 1) with fixed land use types. However, many Asian countries that do not have their own dust prediction models want to use the results of the ADAM model. This calls for an expansion of the model's domain (Fig. 1) and for a model that can be run the whole year round, since Asian dust occurs all year round somewhere in Asian dust source regions. Thus, some parameters in the ADAM model need to be changed to yield more accurate results in predicting other Asian dust events [13].

One of the most important controlling factors for dust emission and intensity is the reduction of vegetation in the source region over time. However, all of the ADAM models mentioned above use time-independent emission reduction factors in the source regions estimated by United States Geological Survey's (USGS) land-use types, even though emission reduction factors can be changed along with changes in surface properties, which are caused by the growth of grasses and trees as well as the expansion of cultivated land in the source regions.

Recently, Park et al. [4] have developed the ADAM2 model, based on the ADAM1 model, with the use of the Normalized Difference Vegetation Index (NDVI), which is known to correlate highly with green biomass and the leaf area index [14-16] and also with the number of dust storm days in the dust source regions [17]. ADAM2 uses temporary variations in threshold wind speeds for dust-rise in each soil type region obtained from re-delineated Asian dust source regions (Fig. 1) and the time-dependent dust emission reduction factors due to vegetation parameterized with the use of Spot/Vegetation NDVI data for the period of 1998 to 2006 [4,13] in the extended model domain (60-160E, 10-60N) (Fig. 1). The limited performance test of this model has been done for dust events observed in Asia during the periods of 29 March to 2 April 2007 and of 29 to 31 December 2007 [4,13]. Some potential capabilities of ADAM2 were revealed in predicting these events. However, further performance tests of ADAM2 are required to be used as an operational forecast model in the Asian domain for the whole year round.

The purpose of this study is to test the capability of

ADAM2 as an operational dust forecast model in the Asian domain. The simulated PM_{10} concentrations by ADAM2 are compared to those observations made at several monitoring sites in the source region of China and the downstream region of Korea for the months of May and December, 2007.

2. Model description

2.1 Meteorological model

The meteorological model used in this study is a fifth-generation mesoscale model of a non-hydrostatic version (MM5, Pennsylvania State University/National Center for Atmospheric Research) defined in the x, y and σ coordinates [18,19]. The model domain has a horizontal resolution of 30 km and 25 vertical layers, including major Asian dust source regions (Fig. 1).

2.2 ADAM model

The ADAM and the ADAM1 models modified from ADAM, are Eulerian dust-transport models that include specifications of dust source regions delineated by a statistical analysis of WMO dust-reporting data and statistically-derived dust emission conditions in sandy, Gobi, Loess and mixed soil surfaces in the domain indicated by the inner rectangle in Fig. 1. The dust emission flux in the ADAM and ADAM1 models is assumed to be proportional to the fourth power of the friction velocity with the modification of land use types in each source-grid region. The ADAM model uses the spectral-mass emission flux of dust being proportional to the power of 1.5 of the particle radius [2], whereas the ADAM1 model uses the suspended particle-size distribution parameterized by the several log-normal distributions in the source regions, based on the concept of minimally and fully dispersed particle-size distributions [20]. Both models have 11 sizes of bins with near the same logarithmic interval for particles of 0.1-37 μm in radius [2,3]. The detailed description on the ADAM and ADAM1 model is given in the references [2,3,6].

The ADAM 2 model [4,13], modified from the ADAM1 model, uses time-dependent threshold wind speeds for dust-rise in the dust source regions delineated by the statistical analysis of the WMO dust reporting data for 9 years (1998 to 2006) in different soil surfaces in the expanded domain, as shown in Fig. 1. This model also uses time-dependent dust emission reduction factors due to vegetation parameterized with the use of the NDVI values for 9 years (1998 to 2006) obtained from the Spot/Vegetation product of the maximum value composite syntheses for a ten-day period in a spatial resolution of 1x1 km^2 (http://free.vgt.vito.be) in the Asian dust source region (Fig. 1).

3. The performance tests of ADAM 2

3.1 Simulations of dust events observed in Korea

The performance of ADAM2 was tested by simulating an Asian dust event as observed in Korea from 31 March to 2 April 2007 and compared to the result of ADAM1 [13]. The results indicated that both models simulated quite well the starting time of the events observed in Korea but the ADAM1 model poorly simulated the duration period and the peak PM_{10} concentration, whereas the ADAM2 model simulated these quite well [13]. Another dust event occurred on 27-31 December 2007 (winter event) in Korea was simulated by ADAM2 [4]. ADAM2 performed well for this case in terms of dust concentrations in the dust source region of China and the downstream region of Korea. However, the starting time of the dust event in the downstream region of Korea lagged by 3-4 hours due to the slow movement of a dust loaded synoptic system [4]. The above case studies indicated that the statistically-derived emission reduction factors due to vegetation with the use of the NDVI value could improve the estimation of dust concentrations of dust events [4].

The performance of the model needs to be tested for dust events and non-dust events in order to be used as an operational model. Therefore, two cases of one-month simulations were conducted with ADAM2 and the results are compared with observed PM_{10} concentrations in the source region of China and the downstream region of Korea.

3.2 A simulation with ADAM2 of Asian dust events during May 2007

The ADAM 2 model simulated the Asian dust events of May 2007 with the use of the NDVI distribution averaged for the month of May for 9 years (1998 to 2006) in the whole Asian domain, as shown in Fig. 1. The statistically obtained emission reduction factors due to vegetation in different surface soil types with time are described in details by Park et al. [4].

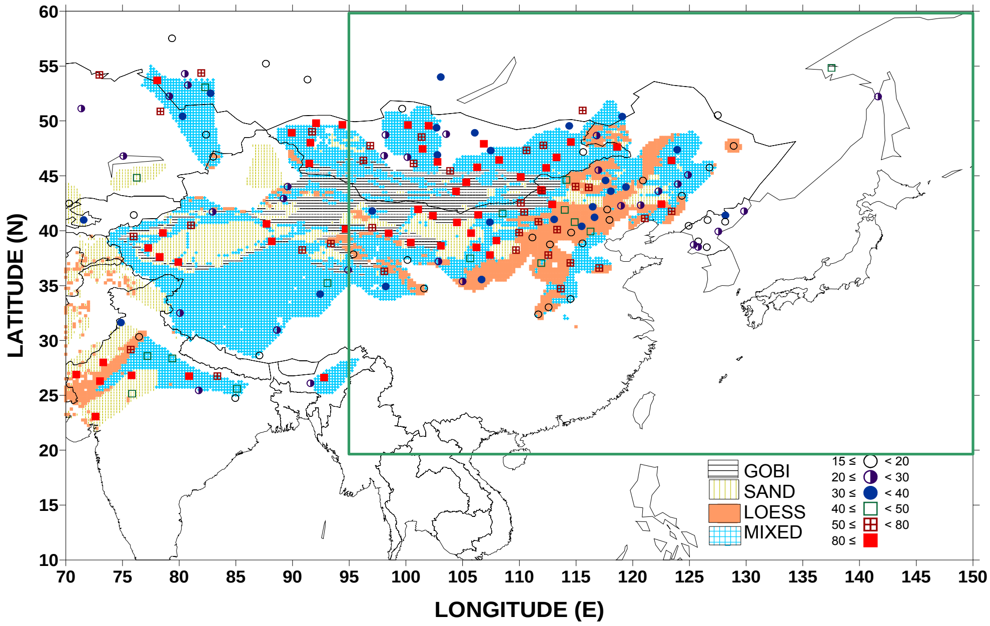

Figure 1. The Model domain with the indication of Asian dust source regions delineated by the occurrence frequencies of dust-rise with WMO 3-hourly reporting data for 9 years (1998-2006). The source region is composed of four different surface soil types: Gobi ( ), sandy ( ), Loess ( ) and mixed soil ( ). The inner rectangle indicates the model domain of ADAM and ADAM1.

The spatial distribution of the averaged NDVI in May is given in Fig. 2 and that of the emission reduction factor due to vegetation (Fig. 3) estimated by the statistically obtained empirical equation in the Asian dust source region [4,13]. Much of the Asian dust source regions in Fig. 1 during May show the NDVI value to be less than 0.2 except in central eastern China over the Loess plateau region, north-eastern China in the mixed soil region, and northern India where the NDVI value is larger than 0.4 (Fig. 2). These features are well revealed in the horizontal distribution of the dust emission reduction factor due to vegetation in Fig. 3. Those regions with the NDVI value less than 0.2 in the dust source region, which indicate bare soil or little vegetation, have zero emission reduction factors due to vegetation whereas dust emissions are significantly suppressed by vegetation in those regions with the NDVI value larger than 0.3 (Fig. 3).

However, the suppression of dust emission due to vegetation depends on not only the coverage of vegetation, but also the surface soil type. The empirically-derived regression equation of the dust emission reduction factors due to vegetation at each soil type in the dust source region for May [4,13] is shown in Fig. 4. This clearly indicates that the NDVI value and the emission reduction factor due to vegetation vary with surface soil types. For example, in May (Fig. 4) if the NDVI value is 0.21, the emission reduction factors are near zero in the sandy, 0.19 in the Loess, 0.20 in the mixed soil and 0.82 in the Gobi regions.

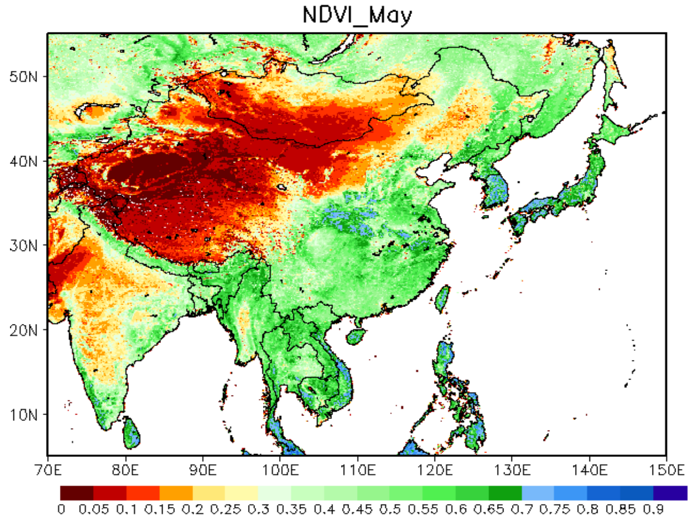

Figure 2. The horizontal distribution of the averaged NDVI value in May with the use of 9-year data (1998 to 2006).

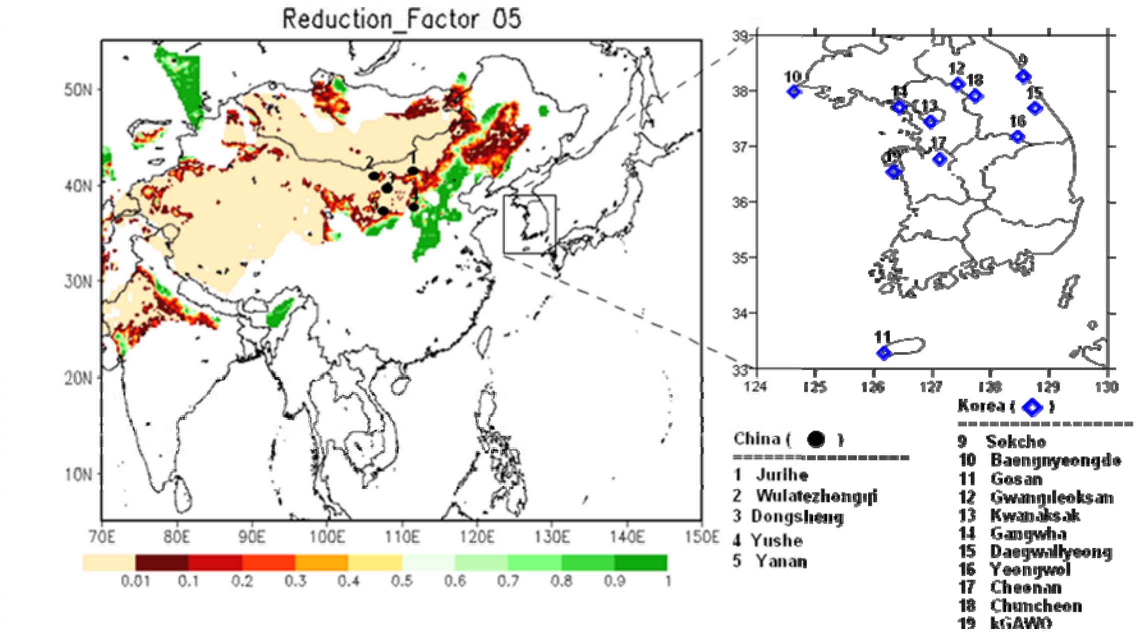

Figure 3. The horizontal distribution of the emission reduction factor due to vegetation in May. The locations of monitoring sites in the source region (numbered site 1-5) and the downstream region of Korea (numbered site, 9-19).

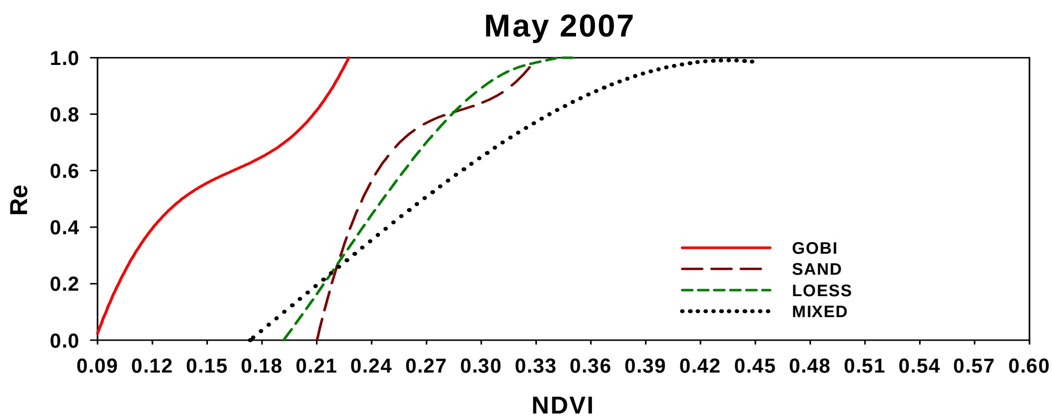

Figure 4. Statistically derived optimal regression equations of dust emission reduction factor (Re) in May at different soil types of Gobi (——), Sand (– – –), Loess (------) and mixed soil (..........).

Fig. 5 shows a time series of observed and simulated PM_{10} concentrations near the surface at several sites located in the dust source region of China (Fig. 3). The model simulated quite well the occurrences of dust storms that were indicated by the high observed surface PM_{10} concentration at all sites in the source region. However, there were some tendencies for the model to slightly underestimate the surface PM_{10} concentration at sites located in the northern part of China, including Jurihe, Wulatezhongqi and Dongsheng, while to slightly overemstimate the surface concentration at sites located in the southern part of the source region, including Yushe and Yanan (Fig. 5).

In the downstream region over Korea, the model excellently simulates the starting and ending times of the dust events observed there (Fig. 6). Three major dust events were observed over Korea in May (Fig. 6). All these events were well-simulated. However, the simulated surface PM_{10} concentration was slightly overestimated at several monitoring sites in Korea (Fig. 6). The non-dust periods in May were also well simulated by the ADAM2 model, suggesting its potential as an operational dust forecast model in the Asian domain.

Fig. 7 shows the horizontal distribution of the modelled surface PM_{10} concentration averaged for the month of May. The averaged surface PM_{10} concentration over the Asian dust source region exceeds 50 $\mu g\ m^{-3}$ with maximum concentration of more than 300 $\mu g\ m^{-3}$ over the border of southern Mongolia and central northern China. The impact of the Asian dust extends to the north-west Pacific to the east, Cambodia and Vietnam to the south, the southern border of Russia to the north and Central Asia to the west.

3.3 A simulation with ADAM2 of Asian dust events during December 2007

The performance test of ADAM2 in winter was conducted by simulating Asian dust events that occurred during December 2007. Fig. 8 shows the horizontal distribution of the NDVI value averaged for December over 9 years (1998 to 2006) of Spot/ Vegetation NDVI data. In most parts of the dust source regions and the high latitude region of Russia except in northern India where the NDVI value is larger than 0.3 due to the subtropical region, the NDVI value is less than 0.15. This suggests dust source regions with a bare soil or little vegetation and covered with snow over the high latitude region, where the dust emission is prohibited as a dust emission condition in the model.

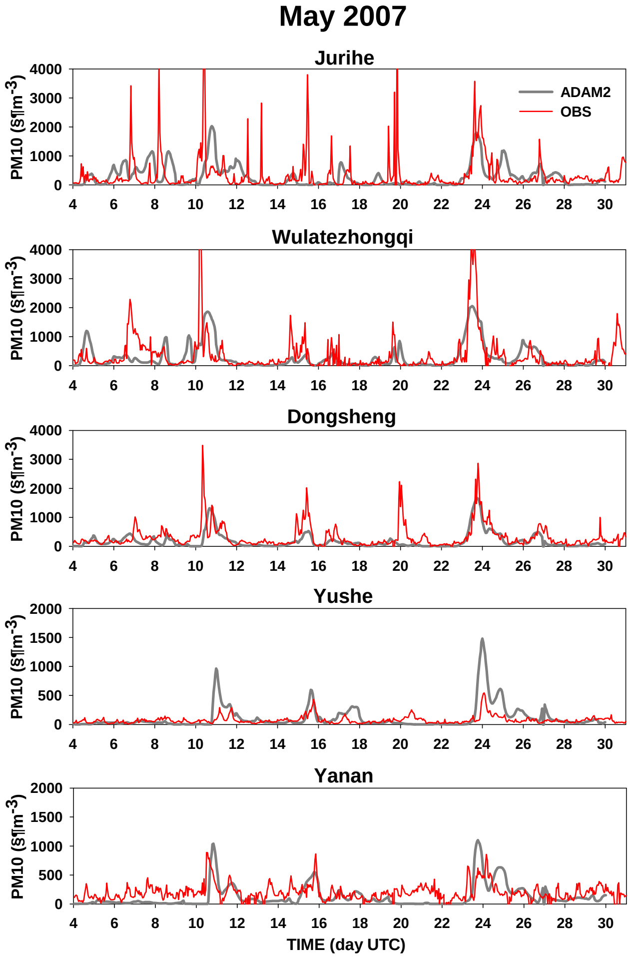

Figure 5. Time series of observed (▬, red) and modeled (ADAM2(▬)) surface PM_{10} concentration ($\mu g\ m^{-3}$) at dust source sites in China in May 2007.

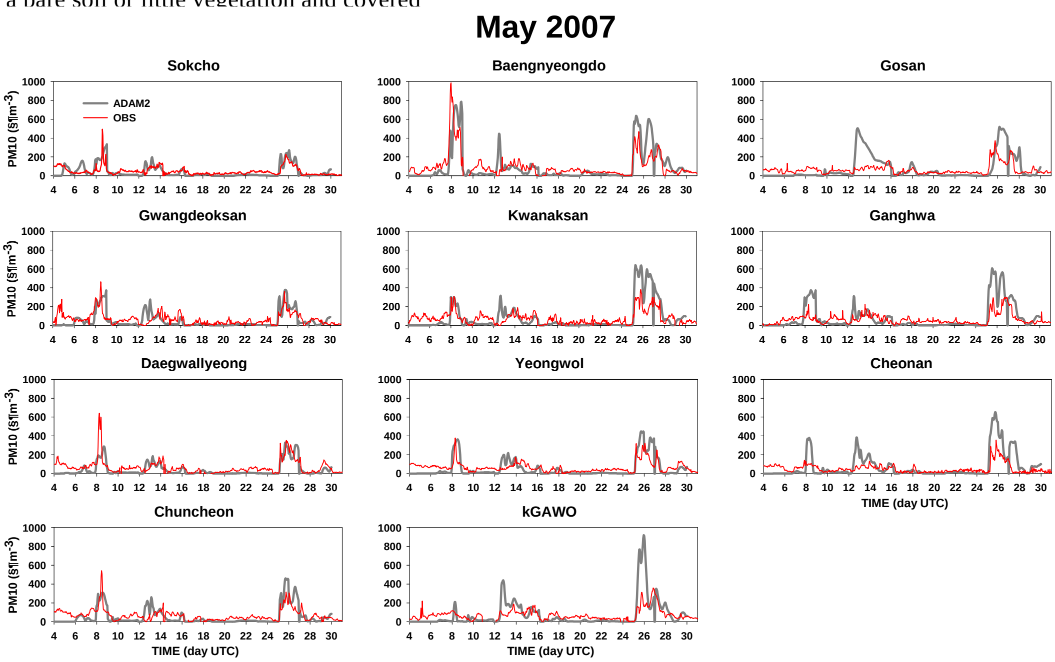

Figure 6. Time series of observed (▬, red) and modeled (ADAM2(▬)) surface PM_{10} concentration ($\mu g\ m^{-3}$) at the downstream sites in Korea in May 2007.

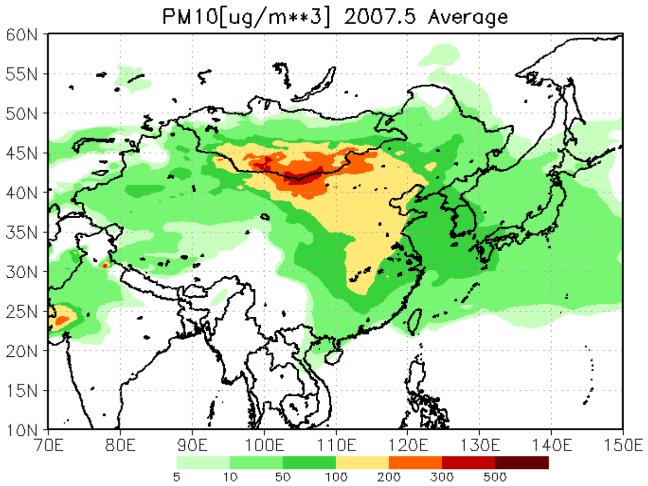

Figure 7. The horizontal distribution of monthly averaged surface PM_{10} concentrations (μg m^{-3}) in May 2007.

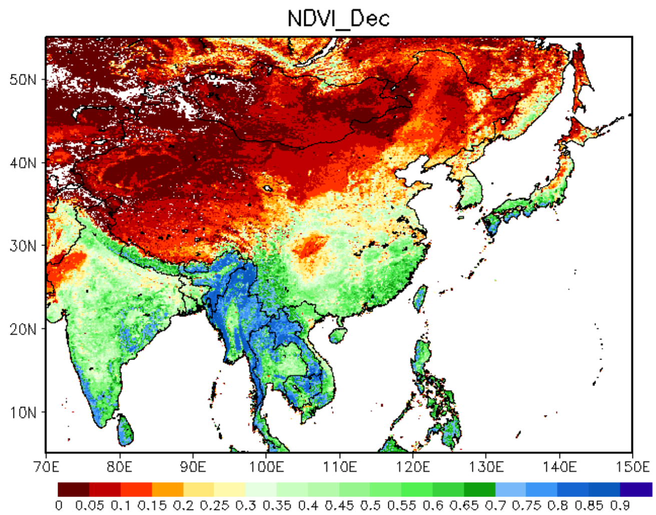

Figure 8. The horizontal distribution of the averaged NDVI value in December with the use of 9-year data (1998 to 2006).

Since the dust source regions are composed of bare or near bare soil during the winter time, the upper limit value of the NDVI for the dust-rise is the same as the free NDVI value (FNV) [4,13]. The FNV is 0.09 in the Gobi, 0.21 in the sandy, 0.19 in the Loess and 0.17 in the mixed soil regions. If the NDVI value at a grid exceeds the FNV defined at each soil and that is 0.00 on the snow covered surface, dust cannot rise in that grid.

Fig. 9 shows the horizontal distribution of dust emission reduction factors due to vegetation estimated with the above-mentioned condition. The most parts of dust source regions are not affected by vegetation in December except for the regions of northwestern India and central eastern China over the Loess region (Fig. 9).

With the use of the horizontal distribution of the December mean NDVI (Fig. 8) and the emission reduction factor due to vegetation (Fig. 9), the events of December 2007 was simulated with ADAM2. Fig. 10 shows the time series of the observed and the simulated PM_{10} concentration near the surface at several monitoring sites in the source region (Fig. 3). A severe dust event with the observed maximum dust concentration of 8,000 μg m^{-3} at Jurihe during 27-29 December 2007 was simulated excellently in term of the starting and ending times of the dust storm with the peak concentration occurring time. However, the simulated maximum surface PM_{10} concentration (6,000 μg m^{-3}) during the dust storm period at Jurihe is lower than that of the observation, which is contrary to other monitoring sites, including Wulatezhongqi, Dongsheng, Yushe and Yanan, where the simulated concentrations were slightly higher than that of the observations. Several weak dust events that had occurred during December were also quite well simulated (Fig. 10).

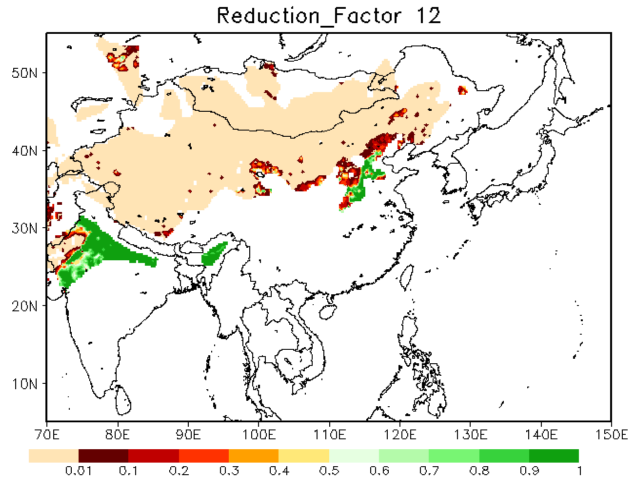

Figure 9. The horizontal distribution of the emission reduction factor due to vegetation in December.

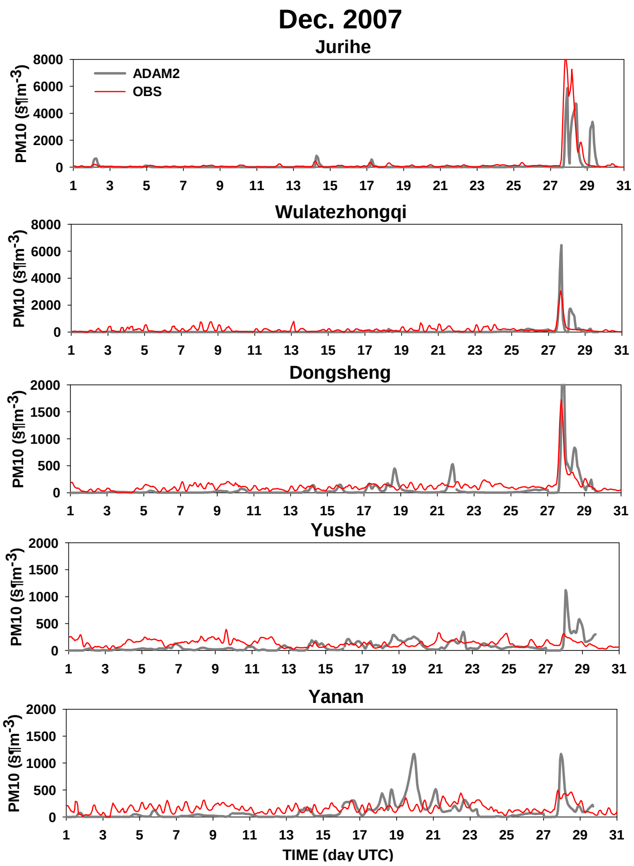

Figure 10. Time series of observed (▬▬, red) and modeled (ADAM2(▬▬)) surface PM_{10} concentration (μg m^{-3}) at dust source sites in China in December 2007.

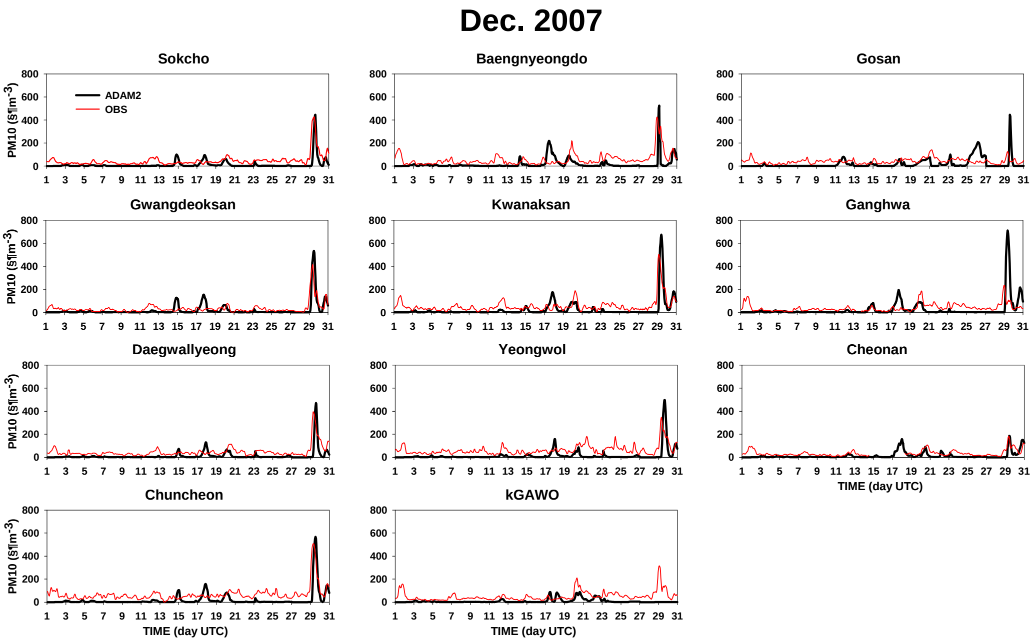

Figure 11. Time series of observed (▬, red) and modeled (ADAM2(▬)) surface PM_{10} concentration (μg m^{-3}) at the downstream sites in Korea in December 2007.

Fig. 11 shows the time series of observed and modeled surface PM_{10} concentrations at sites located in the downstream region of Korea (Fig. 3). A main dust event was observed at all monitoring sites over Korea during 29-30 December in Korea. This event was excellently simulated in terms of the starting and ending times of the dust event and the maximum surface PM_{10} concentration. Several weak dust events and non-dust events observed in Korea were also successfully simulated with ADAM2 (Fig. 11).

The monthly averaged surface PM_{10} concentration simulated by ADAM 2 in December over the dust source region (Fig. 12) is much higher than that in May (Fig. 7) with the westward shift of the maximum surface PM_{10} concentration region over Taklimakan. This clearly indicates that severe dust storms occur more frequently in December (Fig. 12) than in May (Fig. 7) in the northwestern part of the dust source region in China. The impact of dust storms in December extends to about 18°N to the south, the north-west Pacific between 25° and 35°N to the east, the southern border of Russia to the north, and further west to Central Asia.

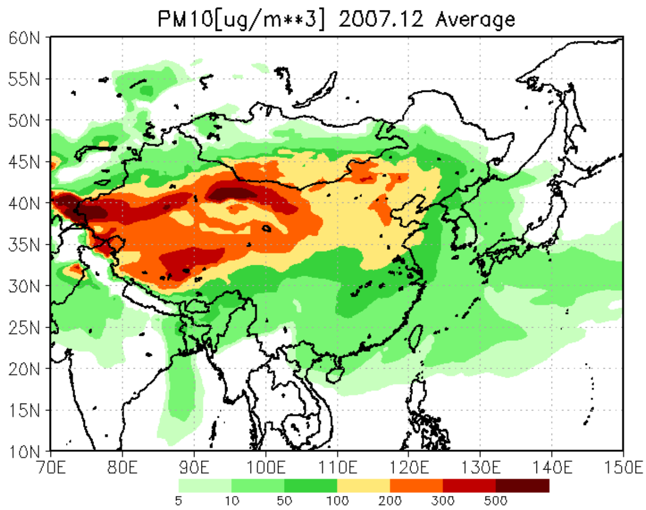

Figure 12. The horizontal distribution of monthly averaged surface PM_{10} concentrations (μg m^{-3}) in December 2007.

4. Conclusion

The performance of the ADAM 2 model was tested as an operational Asian dust forecast model in the Asian domain for the whole year round. The previously conducted performance tests for the couple of dust events observed in Korea and the presently conducted a whole-month period tests in May and December indicate that the ADAM 2 model simulates much better than the ADAM or ADAM 1 model in terms of the dust event starting times, durations and their peak PM_{10} concentrations as observed in Korea. The occurrence and non-occurrence of dust storms in the dust source region in China were well simulated with ADAM 2. However, there were some differences in simulated maximum surface PM_{10} concentrations as compared with observations at some monitoring sites both in the source region of China and the downstream region of Korea. This might be in association with inaccurate simulation of meteorological fields and/or dust emission parameterization in the dust source region.

Recently, dust monitoring towers were installed in the Asian dust source regions of China and Mongolia to measure meteorological parameters including wind speed and direction, relative humidity, air temperature, long and shortwave radiation, precipitation, turbulent intensity, soil temperature, and moisture and ground heat flux with the surface PM_{10} concentration. These data will be used to test the ADAM 2 model more rigorously and to develop a new emission parameterization of dust from dust source regions having different surface soil types.

After a year-long continuous test of ADAM 2 with more accurately observed meteorological parameters and surface PM_{10} concentrations in the source region and the downstream region, the ADAM 2 model will be used as an operational model in the Asian domain all year round.

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data are obtained from the National Institute of Meteorological Research in the Korea Meteorological Administration.

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