Asian dust aerosol models (ADAM)

Parameterization of dust emission reduction factors

Soon-Ung Park, Anna Choe, Moon-Soo Park and Eun-Hee Lee

The Asian Dust Aerosol Model (ADAM) in the Korea Meteorological Administration (KMA) was developed in 2003 as an operational forecasting model. It was first modified to ADAM1 based on dust source regions in northern China. Later still it was modified to ADAM2, with enhanced ability to deliver timely and quality sand and dust storm forecastings to all Asian countries that might be affected by dust storms. ADAM2 model utilizes a Normalized Difference Vegetation Index (NDVI) obtained from spot vegetation data. This article discusses the usefulness of these data and the capability of ADAM2 as an operational dust forecast model in the Asian domain the whole year round.

Soon-Ung Park
Anna Choe
Moon-Soo Park
Center for Atmospheric and Environmental Modelling, Seoul National University Research Park, Rm 515, San 4-2, Bongcheon-dong, Kwanak-gu
Seoul, 151-818, Republic of Korea
Tel: (+82-2) 885 6712
Fax: (+82-2) 885 6715
E-mail: supark@snu.ac.kr
Eun-Hee Lee
Seoul National University
Seoul 151-741, Republic of Korea

Introduction

Asian dust, called *Hwangsa* in the Republic of Korea and *Kosa* in Japan, is a typical example of mineral aerosol frequently originating in the Gobi desert, other sand deserts, the loess plateau and the barren mixed soil in northern China and Mongolia during the spring season.[1, 2, 3] Dust storms occurring in East Asian desert regions tend to cause major aerosol events well beyond the Asian continent.[4] The occurrences of strong dust storms are often associated with catastrophic consequences to humans and their environment. Indeed, very severe dust storms were observed in the Republic of Korea from 21 to 23 March and from 7 to 9 April 2002.[3] During these periods the observed PM_{10} concentrations were over 1,500 ì g/m^3 at most monitoring sites in the Republic of Korea, causing natural disasters, including temporary closing of most airports and elementary schools in the country.[3]

In 2002, the Asian Dust Aerosol Model (ADAM) was developed on the basis of a statistical method of dust emission conditions, using the World Meteorological Organization's 3-hourly synoptic reporting data for seven years from 1996-2002 in the source region.[2, 5] The ADAM model successfully simulated the temporal and spatial distribution of dust concentration and the starting and ending times of Asian dust events observed in the Republic of Korea during 21-22 March and 7-9 April 2002.[2, 3]

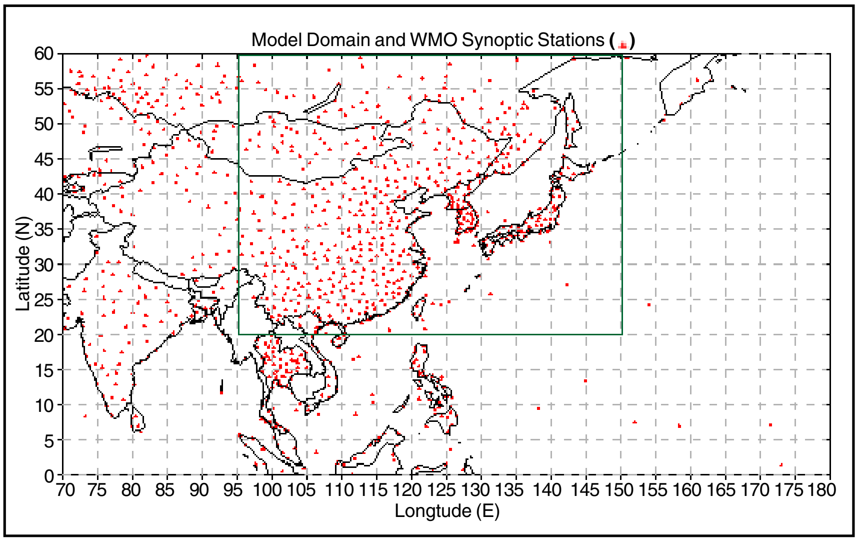
An ADAM1 model has been developed, based on the ADAM model, by taking into account observed monitoring tower data at Duolun in Inner Mongolia and the changes in land-use types in the source regions.[6] This model has been able to simulate quite reasonably the Asian dust events observed in the Republic of Korea since 2003.[6]

Both ADAM and ADAM1 use the total dust emission flux parameterized for Saharan dust outbreaks,[7, 8] where sandy soil predominates. However, the Asian dust source regions are composed of gobi, sand, loess and mixed soils;[1, 2, 3, 4, 5] so one type of soil may not be relevant in estimating the volume of dust emission. To take into account different soil types, saltation fluxes[9] have been used for the parameterization of the total dust emission flux from different source regions[10] with the observed clay content in each soil type. The newly parameterized total dust emission flux was capable of simulating the starting and ending times of dust events and the maximum dust concentrations observed in the Republic of Korea slightly better than those results of the ADAM1 model.

ADAM1 as an operational model to forecast dust events in the Korea Meteorological Administration (KMA) has been used mainly to forecast dust events over the Republic of Korean peninsula during the spring season, when the frequency of observed Asian dust events in the Republic of Korea is the highest. The model therefore uses a rather small domain (20-60°N and 95-150°E) (Figure 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 domain (Figure 1) and for a model that can be run the whole year round, since Asian dust occurs all year round somewhere or the other in Asian dust source regions. Therefore, some parameters in the ADAM model need to be changed to yield more accurate results in predicting other Asian dust events.

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 the ADAM models mentioned above use time-independent emission reduction factors in the source regions, estimated by USGS land-use types, even though emission reduction factors can be changed along with changes in surface properties, caused by the growth of grasses and trees and the expansion of cultivated land in the source regions.

Figure 1: The domain of the model and the distribution of WMO synoptic stations. The inner rectangle is the domain of ADAM and ADAM1



Recently, remote sensing has been applied to monitor the desertification and to access the amount of vegetation in arid and semi-arid regions.[11, 12] Satellite vegetation monitoring using red and near infrared channels has been one of the most widely used indices of change of vegetation coverage.[13] The Normalized Difference Vegetation Index (NDVI) is known to correlate highly with green biomass and the leaf area index.[14, 15, 16] Also, the number of dust storm days is known to have a correlation with NDVI in spring, especially in central and east Inner Mongolia in their inter-annual variation.[17]

This article discusses the potential of the ADAM2 model for Asian dust forecasting with a time-dependent dust emission reduction factor due to vegetation in the dust source region with the use of Spot/Vegetation NDVI data.

Normalized difference vegetation index (NDVI)

The spot/vegetation product of Maximum Value Composite Syntheses (MVC) acquired in a ten-day period in a spatial resolution of 1×1 km^2 in the Asian domain (Figure 1) can be obtained from the site http://free.vgt.vito.be.

The Spot 4 satellite has four vegetation spectral bands: the blue (BLU: 0.43-0.47 μm), the red (RED: 0.61-0.68), the near infrared (NIR: 0.78-0.89) and MIR (1.58-1.75).

The normalized difference vegetation index (NDVI) from Spot 4/vegetation satellite datasets is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

with the pixel brightness count in the sea area being set to 0.[18]

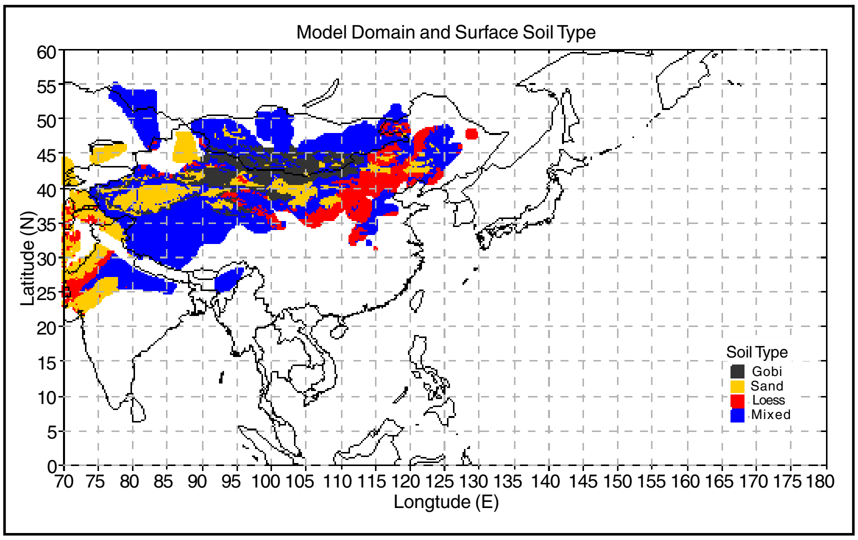
WMO synoptic data

Three-hourly reports of present weather, weather codes of 07 (blowing sand) and 08 (dust whirl) and wind speed at the WMO regular reporting stations in the domain of 70-180°E and Equator-60°N (Figure 1) for nine years from 1998 to 2006 have been analyzed to identify occurrence locations and frequencies of Asian dust storms and dust rises. There are 821 regular reporting stations in the study domain (Figure 1).

Model description

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 ó coordi

Figure 2: Spatial distribution of surface soil types (1: Gobi, 2: Sand, 3: Loess, 4: Mixed) in the Asian dust source region



nate.[19, 20]. The model domain (Figure 1) has a horizontal resolution of 30 km and 25 vertical layers including major Asian dust source regions (Figure 2).

The ADAM model is a Eulerian dust-transport model that includes specifications of dust source regions, delineated by a statistical analysis of WMO dust-reporting data and statistically derived dust emission conditions in sand, gobi, loess and mixed soil surfaces in the domain indicated by the inner rectangle in Figure 1. The dust emission flux in the ADAM model is assumed to be proportional to the fourth power of the friction velocity due to modifications of land use types in each source-grid region. The ADAM model uses the suspended particle-size distribution parameterized by the several log-normal distributions of the soil particle-size distribution in the source regions, based on the concept of minimally and fully dispersed particle-size distribution. It has 11 sizes of bins with the same logarithmic interval for particles of 0.1-37 ì m in radius.[2, 3]

This model was modified to the ADAM1 model with the use of the concept of minimally and fully dispersed parent soil particle-size distribution[21, 22], for the suspended particle-size distribution[3] and the observed meteorological parameters in the dust source regions in northern China.[23] However, the model domain of the ADAM and the ADAM1 model is restricted in the East Asian domain (95-150 °E and 20-60 °N) so that the models can be used as a forecasting model in the whole Asian domain.

Recently[24] the model domain has been expanded to include the whole Asian domain (Figure 1) and the Asian dust source region is delineated by using the spatial distribution of the total number of dust-rise reporting days for nine years from 1998 to 2006 at the WMO surface reporting stations within the expanded domain. The horizontal distribution of the total number of dust-rise occurrence days more than 14 days during last 9 years is used as the dust source regions of the ADAM2 model.[24]

There are 167 WMO regular reporting stations in the Asian dust source region with four different types of surface soils (Gobi, Sand, Loess and Mixed soil) in the dust emission regions, of which 24, 29, 35 and 79 stations are located in the Gobi, Sand, Loess and Mixed soil regions, respectively (Figure 2).

The threshold wind speed for the dust rise in ADAM2

Table 1 shows the monthly variation of the threshold wind speed for the dust rise at each different surface-soil type used in the ADAM2 model.[24] This has been determined by examining the frequencies of wind speed occurrence; the dust-rise with respect to the wind speed; the ratio of the occurrence frequency of dust rise to that of the wind speed; and the normalized cumulative ratio of the occurrence frequency of the dust-rise to that of the wind speed in various soil-type regions; for each month of a period of nine years (1998 to 2006). The threshold winds speed was defined as the wind speed at the normalized cumulative ratio of the dust occurrence frequency being 3.5 per cent.[2] Very few dust-rise occurrence frequencies was observed in the Loess region for the period of July to October.

Monthly variation of the upper limit value of NDVI in the Asian dust source region

The ADAM2 model uses the NDVI values obtained from spot/vegetation product of the maximum value composite syntheses (MVC) for a ten-day period in a spatial resolution of 1×1 km^2 (http://free.vgt.vito.be/) in the Asian dust source region (Figure 2). From these data 9-grid cells of data centred at each WMO surface reporting station were retrieved for 9 years, from 1998 to 2006, to find occurrence frequency of the NDVI value with respective to the NDVI value in an interval of 0.01 in each surface soil type region (Figure 2). From out of these the NDVI data are chosen when the wind speed reported at that station exceeds the threshold wind speed in Table 1, and then the distribution of the occurrence frequency of the NDVI value with respect to the NDVI value in an interval of 0.01 is made for each month. The upper limit value of NDVI is determined as the NDVI value at the normalized cumulative NDVI occurrence frequency, being 99 per cent for each month in each surface-soil type region.

Figure 3 shows the monthly variation of the mean upper limit value of NDVI in regions having different soil-types. During the winter time, from November to March, the upper limit value of NDVI is almost constant in each region - with a minimum of 0.10 in the gobi region and a maximum of 0.27 in the loess region. As the season progresses the upper limit value of NDVI reaches a maximum value of 0.59 (in July and August) in the gobi region, 0.77 (in August) in the sand region and 0.77 (in July) in the mixed soil region. This may be associated with the growth of vegetation in these regions.

Similar analyses have been done for dust occurrence frequency with respect to the NDVI value in an interval of 0.01. The result is also shown in Figure 3 as dashed lines. The upper limit value of NDVI for the dust occurrence frequency varies quite similarly to that for the NDVI occurrence frequency (solid lines in Figure 3) but has a much lower value during the vegetation-growing season in each soil-type region. These differences imply the reduction of dust occurrence probability due to vegetation in each soil-type region.

It is worth noting that, during winter time, when the vegetation is minimum (or the soil is even bare) the upper limit value of NDVI for dust occurrence frequency is a minimum. However, the minimum value varies with the type of surface soil. This allows us to define a “free NDVI value (FNV)” for each soil type. In other words, this is the upper limit value of NDVI for dust occurrence without the impact of vegetation. Table 2 shows the free NDVI value for dust occurrence for each soil type region.

Parameterization using NDVI values

Vegetation in a dust source region reduces the occurrence of dust events (Figure 3). The impact of vegetation on dust occurrence can be estimated by analyzing the occurrence frequencies of NDVI value and the dust rise in the NDVI range from the free NDVI value (FNV) (Table 2) to the upper limit value of NDVI for the dust occurrence (Figure 3).

Figure 4 shows for example the procedure to get the dust occurrence probability density function (P_0) affected by the vegetation in a sand soil-type region in May. Distributions are constructed of normalized NDVI occurrence frequency that exceed the threshold wind speed (Figure 4a) and normalized dust occurrence frequency (Figure 4b) in a range from FNV to the upper limit value of NDVI for the dust occurrence (UNV), in intervals of 0.01. Then the dust occurrence probability function (Figure 4c) is calculated by dividing the distribution function of the normalized dust occurrence frequency (Figure 4b) by that of the normalized NDVI occurrence frequency

Table 1: Monthly variations of threshold wind speed (m/sec) in each soil-type region. The value used in the ADAM model is also listed.

Soil/Month	Gobhi	Sand	Loess	Mixed
1	8.0	7.5	6.0	7.5
2	8.0	7.5	6.0	7.5
3	7.0	7.5	6.0	7.5
4	7.0	6.0	5.5	6.0
5	7.0	6.0	5.0	6.0
6	7.0	6.0	5.0	6.0
7	7.0	6.0	—	6.0
8	7.0	6.0	—	6.0
9	7.0	6.0	—	7.5
10	7.0	6.0	—	7.5
11	8.0	7.5	7.5	7.5
12	8.0	7.5	7.5	7.5
ADAM	9.5	7.5	6.0	9.2

Figure 3: Monthly variations of the upper limit value of NDVI determined by the threshold wind speed (solid lines) and by the dust occurrence frequency (dashed lines) in the Gobi (—●—, --○--), Sand (—▲—, --△--), Loess (—■—, --□--) and Mixed soil (—★—, --☆--) regions.

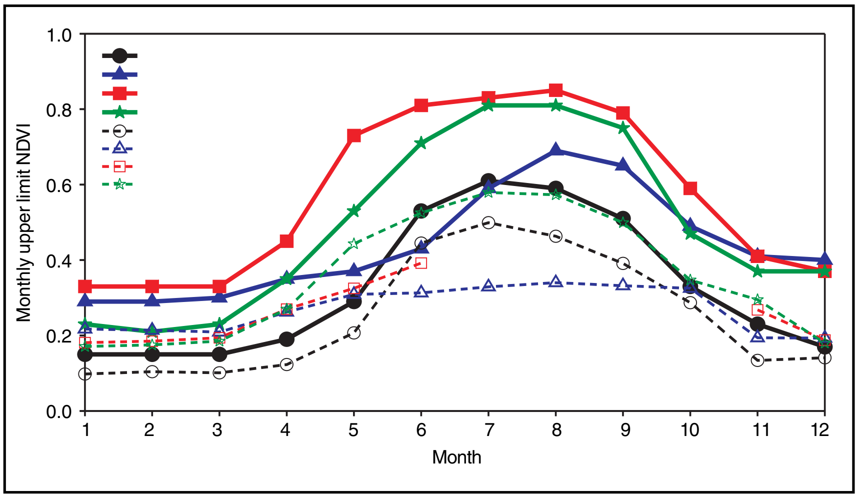


Table 2: Free NDVI value (FNV) in each soil-type region

Soil type	Gobi	Sand	Loess	Mixed
FNV	0.09	0.21	0.19	0.17

(Figure 4a). The probability density function (Figure 4d) affected by vegetations is obtained as the cumulative probability function of the dust occurrence probability function in Figure 4c. The analytical dust occurrence probability density function (P_0) is obtained by fitting a cubic spline function to the distribution of the cumulative probability density function to satisfy the conditions of P_0=1 at FNV and P_0=0 at UNV. The same method can be employed in regions with other soil types to get the function P_0.

Thus the dust emission reduction factor R is given by

Figure 4: Normalized percentage occurrence frequencies of (a) wind speed exceeding threshold wind speed and (b) dust rises, (c) percentage ratio of (b) to (a), and (d) cumulative dust occurrence probability function in sand soil-type region.

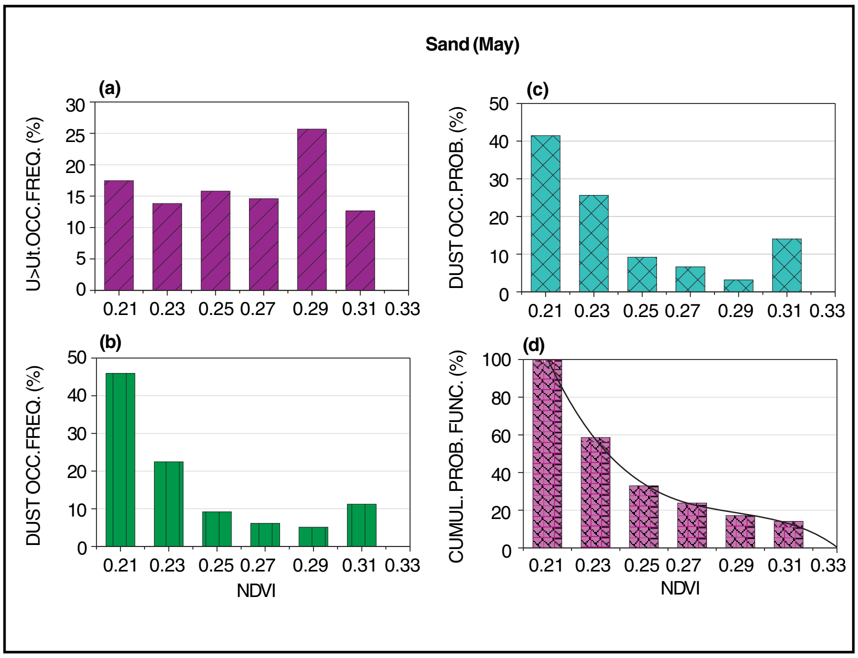
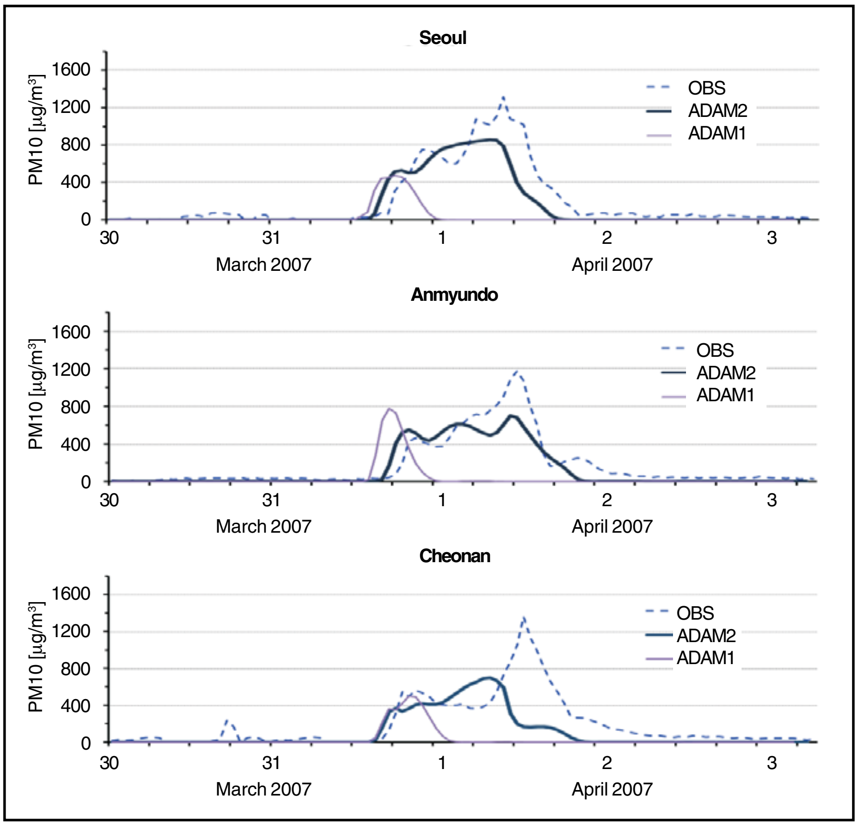


Figure 5: Time series of ADAM1, ADAM2 and observed PM10 concentration (per m³) at (a) Seoul, (b) Anmyundo (c) Cheonan in Republic of Korea



$$R = \begin{cases} 0 & \text{for } NDVI \le FNV \\ 1 - P_0 & \text{for } FNV < NDVI < UNV \\ 1 & \text{for } NDVI \ge UNV \end{cases}$$

Statistically determined dust occurrence probability density functions in the NDVI range, from FNV to UNV with the R^2 value are available.[24] This allows us to run the model all year round using a different reduction factor in each month in each soil-type region, something that cannot be obtained in the ADAM model.

Implementation of ADAM2

The ADAM2 model simulated an Asian dust event, observed in the Republic of Korea from 31 March to 2 April 2007, with the use of the NDVI distribution averaged for the period 21 March to 10 April in 2007 in the Asian dust source region, using FNV and UNV for all surface soil types in this period.[24]

Figure 5 shows time series of observed and simulated PM_{10} concentrations at several sites in the Republic of Korea. The simulation has been done with ADAM1 (thin solid line in Figure 5) and ADAM2 (thick solid line in Figure 5). Both models simulated quite well the starting time of the Asian dust event observed in the Republic of Korea. The presently modified ADAM2 model simulates quite well the first peak concentration but the second maximum peak concentration is much underestimated at all sites, with a shorter duration of the dust event (Figure 5). This is due mainly to the inaccurate simulation of the meteorological field, suggesting that the ADAM2 model has a great potential to be used as an Asian dust forecasting model in the whole Asian domain with more accurate meteorological fields.

Conclusion

ADAM2 was developed to forecast Asian dust events in the whole Asian domain (70°-180°E and Equator-60°N), with temporary variations in threshold wind speeds for dust-rise in each soil-type region and the time-dependent dust emission reduction factor due to vegetation, with the use of Spot/Vegetation NDVI data for the period of 1998 to 2006.

The modified ADAM2 model from the operational ADAM1 in KMA is capable of simulating severe dust events occurring in Asian dust source regions all year round.

After several performance tests of ADAM2, the forecasting results of this model will be available on the web (http://www.kma.go.kr) in the near future. Then it can be used for the mitigation of adverse impacts of Asian dust storms in all Asian countries.

Acknowledgement

This work was funded by the Korea Meteorological Administration Research and Development Programme under Grant CATER 2008-3208.

References

1. In H.-J. and Park S.-U. (2002), 'A simulation of long-range transport of yellow sand observed in April 1998 in Korea.' *Atmospheric Environment*, Vol. 36, pp. 4173-4187.
2. Park S.-U. and In H.-J. (2003), 'Parameterization of dust emission for the simulation of the Yellow Sand (Asian dust) observed in March 2002 in Korea'. *Journal of Geophysical Research,* 108, (D19) 4618, doi:10.1029/2003JD00348.
3. Park S.-U. and Lee E.-H. (2004), 'Parameterization of Asian dust (Hwangsa) particle-size distributions for use in dust emission model.' *Atmospheric Environment*, Vol. 38, pp. 2155-2162.
4. Husar R. B., Tratt D. M., Schichtel B. A., Falke S. R., Li F., Jaffe D., Gassó S., Gill T., Laulainen N. S., Lu F., Reheis M. C., Chun Y., Westphal D., Holben B. N., Gueymard C., McKendry I., Kuring N., Feldman G. C., McClain C., Frouin R. J., Merrill J., DuBois D., Vignola F., Murayama T., Nickovic S., Wilson W. E., Sassen K., Sugimoto N., Malm W. C. (2001), 'Asian dust events of April 1998,' *Journal of Geophysical Research* Vol. 106 (D16), pp. 18317-18330, doi:10.1029/2000J D900788.
5. In H.-J. and Park S.-U. (2003), 'The soil particle size dependent emission parameterization for an Asian dust (Yellow Sand) observed in Korea on April 2002,' *Atmospheric Environment*, Vol. 37, pp. 4625-4636.
6. Lee E.-H., Park S.-U. (2005), 'A numerical simulation of an Asian dust (Hwangsa) event observed in Korea on March 10-12, 2004 using the modified ADAM model,' *Advances in Geosciences*, Vol. 5, pp. 67-76.
7. Westphal D. L., Toon O. B., Carlson T. N. (1987), 'A two-dimensional Investigation of the dynamics and microphysics of Saharan dust storms.' *Journal of Geophysical Research*, Vol. 92, pp. 3027-3049.
8. Gillette D. A. (1981), 'Production of dust that may be carried great distances,' *Spec. Pap. Geol. Soc. Am.*, Vol. 186, pp. 11-26.
9. Marticorena B. and Bergametti G. (1995), 'Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme,' *Journal of Geophysical Research*, Vol. 100, pp. 16515-16430.
10. Park S.-U. and Lee E.-H. (2005), 'A numerical simulation of an Asian dust event observed in Korea on 20-22 April 2005 with the ADAM2 model,' *Proceedings of 11th International Joint Seminar on Regional Deposition Processes in the Atmosphere*, November 23-25 2005, Jeju, Korea.
11. Huang S. and Siegert F. (2006), 'Land cover classification optimized to detect areas at risk of desertification in North China', based on Spot Vegetation imagery, *Journal of Arid Environment*, Vol. 67, pp. 308-327.
12. Tucker C. J., Dregne H. E., Newcomb W. W. (1991), 'Expansion and contraction of the Sahara desert between 1980-1990.' *Science,* Vol. 253, pp. 299-301.
13. Telesca L. and Lasaponara R. (2006), 'Vegetation patterns in burned and unburned areas investigated by using the detrended fluctuation analysis,' *Physica A*, Vol. 368, pp. 531-535.
14. Wu B. and Liu C. (2000), 'Crop growth monitor system with coupling of AVHRR and VGT Data,' *Vegetation 2000*, Lake Maggiore, Italy.
15. Lu L., Li X., Huang C. L., Ma M. G., Che T., Bogaert J., Veroustaraete F., Dong Q. H., Ceulemans R. (2005), 'Investigating the relations between ground-measured LAI and vegetation indices in an alpine meadow, north-west China,' *International Journal of Remote Sensing*, Vol. 26 (20), pp. 4471-4484.
16. Wang Q., Adiku S., Tenhunen J., Granier A. (2005), 'On the relationship of NDVI with leaf area index in a deciduous forest site,' *Remote Sensing of Environment*, Vol. 94, pp. 244-255.
17. Zou X. K. and Zhai P. M. (2004), 'Relationship between vegetation coverage and spring dust storms over northern China,' *Journal of Geophysical Research,* Vol. 109, D03104, doi:10.1029/2003JD003913.
18. Duchmin B., Maisongrande P., Dedieu G., Leroy M., Roujean J. L., Bicheron P., Hautecoeur O., Lacaze R. (2000), 'A 10-days compositing method accounting for bidirectional effects.' *Proceedings of the Vegetation 2000*, pp. 313-318, Belgirate Italy.
19. Grell G. A., Dudhia J., Stauffer D. R. (1994), 'A description of the 5th generation Penn State/NCAR mesoscale model (MM5).' *NCAR TECH.* Note NCAR/TN-398, 117pp.
20. Dudhia J., Grill D., Guo Y.-R., Hausen D., Manning K., Wang W. (1998), *PSU/NCAR mesoscale modeling system tutorial class notes (MM5 modeling system version 2).*
21. Lu H. and Shao Y. (1999), 'A new dust model for dust emission by saltation bombardment,' *J. Geophys*, Res. 104, pp. 16827-16841.
22. Shao. Y., Jung E. J. and Leslie L. M. (2002) 'Numerical prediction of Northeast Asian dust storms using an integrated wind erosion modeling system,' *J. Geophys.* Res. 107, 4814.
23. Park S.-U. (2008), 'Asian Dust Aerosol Modeling,' *GEOSS Workshop on Air Quality and Human Health, BICC*, 2 July, Beijing, China
24. Park S.-U., Choe A., Lee E.-H., Park M.-S., Song X. (2008), *The Asian Dust Aerosol Model 2 (ADAM2) with the use of Normalized Difference Vegetation Index (NDVI) obtained from the Spot4/Vegetation data*, submitted to Theoretical and Applied Climatology. ❐