# LONG RANGE TRANSPORT OF ASIAN DUST FROM DUST STORMS AND ITS IMPACT ON JAPAN

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**Abstract.** We simulated the long range transport of dust emitted from dust storms that occurred in China by using a global three-dimensional chemical transport model. A modified dust emission flux scheme and a nonlocal diffusion scheme for determining the atmospheric eddy diffusivity in the atmospheric boundary layer were implemented to improve the chemical transport model. We examined the dust transport by comparing the model results with TOMS satellite images. The model calculated monthly total deposition of dust masses were used for comparison with the measurements collected at sampling stations in Japan, and good agreement was found. The model generally reproduced the temporal and spatial variations of dust reasonably well.

**Keywords:** Aeolian dust, atmospheric transport, dust storms, global model, Kosa

## 1. Introduction

There is a growing interest in atmospheric aerosols due to their significant modification of the photochemical processes, and the important role they played in atmospheric radiation related to the earth's radiative budget for studying global climate change (Penner *et al.*, 2001). The main sources of aerosols affecting global climate change can be classified as: (1) the anthropogenic sources of aerosols derived from fossil fuel emissions and other industrial activities, biomass burning, and agricultural emissions; and (2) the natural sources of aerosols containing the sea salt, ocean dimethylsulfide, and surface dust emissions. In this study, we considered the transport of the natural sources of aerosols associated with the re-suspension of surface dust from large-scale desert areas during dust storms. The re-suspended dust not only affects the atmospheric radiation, but also causes the degradation of visibility in the air, and the deposition of dust mass on the surface transported from one place to another or from the continent to the ocean.

In the springtime from March to May, large-scale dust storms always develop in western and northern China. These dust storms, called Kosa, are associated with strong surface winds in the western part of China, Siberia, and southern Mongolia. During the Kosa, the dust aerosols (i.e., Yellow Sand or Aeolian) are uplifted as high as 6 km (Iwasaka *et al.*, 1988), and transported thousands of kilometers to eastern China, Korea, Japan, and out into the Pacific Ocean (Kotamarthi and

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Carmichael, 1993; Husar *et al*., 2001; Uno *et al*., 2001). These dust aerosols significantly impact the regional climate, visibility, terrestrial ecosystem, and surface dust deposition, as indicated at The First Aeolian Dust Experiment on Climate Impact Workshop (2002). Sokolik *et al*. (2001) gave an excellent review of the current experimental and theoretical approaches on radiative impacts of dust.

The objectives of this study were to improve the estimates of the dust emission flux and the turbulent diffusion responsible for the mixing of dust particles in the atmospheric boundary layer in order to understand the transport of dust during the Kosa in China and its impact on Japan.

## 2. Description of the Model

For this study, we used the global Chemical Transport Model (CTM) that was developed by the Japanese Meteorological Research Institute (MRI) (Tanaka *et al*., 2002). The CTM is linked with the improved general circulation model, MRI/JMA98 that merged MRI's and the Japan Meteorological Agency's (JMA) general circulation models (Shibata *et al*., 1999). The physical processes of convection, including the formations of cloud and precipitation, atmospheric radiation, subsurface hydrology, and vertical diffusion are included in the MRI/JMA98. To calculate the surface eddy fluxes, the method of Louis (1979) is used in the MRI/JMA98. For this study, the improved method for calculating surface eddy fluxes (Lee, 1997) was implemented. An analysis with nudging was used for producing a realistic meteorological data in the MRI/JMA98.

The CTM is an on-line transport model that runs simultaneously with the MRI/JMA98. The 'on-line' means that in each time step we run the MRI/JMA98 to generate the diagnostically meteorological data and the data are immediately used as input in CTM for studying the transport of dust. The CTM as used here is for solving the atmospheric transport-diffusion equation for mineral dust of aerosol. The current CTM is a three-dimensional grid model with a spatial resolution of 2.8°×2.8°, and 30 vertical layers in a $\sigma$-pressure coordinate from the ground surface to 0.4 hPa just above the stratopause. The CTM uses a semi-Lagrangian technique for advection transport and a finite difference scheme for the calculation of vertical diffusion. In the following section of 4, the improved method for describing the atmospheric eddy diffusivity for diffusion in the atmospheric boundary layer was also implemented in the CTM.

For wet deposition scheme, a simple process that was still used by most modelers, was adopted here (Junge and Gustafson, 1957). The process was to remove the aerosol through the wet scavenging in which the removal rate due to rainout was proportional to the aerosol's concentration. The microphysical processes for aerosol coagulation and condensation were not included for the calculations. In this study, we considered only the gravitational settling that is a dominant force for dry deposition process. In the future, we will include the aerodynamic and quasi-laminar resistances to improve the dry deposition process for fine particles.

## 3. Dust Emission Flux

The current CTM uses the scheme of Takemura *et al.* (2000), of dust emission flux based on the empirical approach of Gillete (1978). In the scheme, the dust emission flux is calculated by the wind speed, $U_{10}$, at the height of 10 m, and the threshold wind velocity, $u_t$ that is set to be 6.5 m $s^{-1}$. Many researchers (e.g., Chang *et al.*, 1996; Phadnis and Carmichael, 2000) have used a constant threshold wind velocity for calculating dust emission. Hence, the determination of the threshold wind velocity is critical for calculating the dust emission flux. Since the threshold wind velocity depends on the particle size and soil moisture (Pye, 1989), the scheme was modified here to consider the particle diameter ($\phi_p$), particle density ($\rho_p$), air density ($\rho_a$), and the surface wetness ($w_s$) by adopting the approach of Ginoux *et al.* (2001) in determining the threshold wind velocity, that is,

$$u_t = \begin{cases} 6.5\sqrt{\dfrac{(\rho_p - \rho_a)}{\rho_a} g \Phi_p} \left(1.2 + 0.2 \log_{10} w_s\right) & \text{for } w_s \leq 0.5 \\ \propto & \text{otherwise} \end{cases} ,$$

where $g$ is the acceleration of gravity.

Based on the empirical formulation by Gillete and Passi (1988), the dust emission flux, $F$ (kg $m^{-2}$ $s^{-1}$), can be estimated from the following expression:

$$F = C \left[ u_*^4 \left( 1 - \frac{u_{*,t}}{u_*} \right) \right] \quad \text{for } u_* \geq u_{*,t} ,$$

where $u_*$ and $u_{*,t}$ are the friction velocity and the threshold friction velocity, respectively. The constant, $C$, in the above equation was calibrated to be $1.4 \pm 0.1 \times 10^{-6}$ based on the estimated value obtained from Gillete and Passi (1988).

The relationship between the threshold friction velocity, $u_{*,t}$ and the threshold wind velocity, $u_t$ can be expressed as:

$$u_{*,t} = {C_d}^{0.5} u_t ,$$

where $C_d$ is the drag coefficient that is $(0.23/\ln z_s)^2$, and $z_s$ is the height of the anemometer.

The calculation of dust emission flux, $F$, as shown in above equation depends on the value of friction velocity, $u_*$. In this study, $u_*$ was accurately and efficiently calculated by using an improved formulation (Lee, 1997). The Lee's formulation was developed to improve the Louis's (1979) approach that used an iteration method, and had been commonly used by most of the global circulation models. The improved formulation removes the iteration method to efficiently calculate the surface eddy fluxes, $u_*$, thus saving a great deal of computer time in global calculations from a model.

In this study, we considered the land surface as possible dust sources. However, dust emitting into the atmosphere depends mainly on the surface wind speed, friction velocity and the threshold friction velocity, as shown in the above equations.

## 4. Atmospheric Boundary Layer

Turbulence in the atmospheric boundary layer (ABL) can cause a mixing of heat, moisture, momentum, and passive scalars, such as the dust considered here. To parameterize the turbulent eddy fluxes in the ABL, we used the nonlocal diffusion scheme for describing the atmospheric eddy diffusivity (Troen and Mahrt, 1986; Holtslag *et al.*, 1990). The formulation of the nonlocal eddy diffusivity depends on *bulk* properties of the characteristic turbulent velocity scale and the boundary-layer height, rather than local properties, such as a function of a length scale and the local vertical gradient of wind and temperature. Holtslag and Boville (1993) have shown a systematic improvement in global-climate simulations by using nonlocal, rather than local diffusion schemes.

## 5. Model Simulation

We carried out a 13-month model integration from 1 December 1999 to 31 December 2000, initially with a zero mass of dust. Since the CTM is an on-line transport model, the friction velocity based on the approach of Lee (1997) can be calculated by the surface wind and potential temperature, and ground temperature obtained from the MRI/JMA98. The dust emission based on the above equations is then calculated by the friction velocity that exceeds the threshold friction velocity. The model results in the first month were used as the initial input of model integration for the year 2000. After a one-year integration, the results were analyzed and compared with the measurements of total depositions (wet plus dry) of dust collected at the aerosol sampling stations in Japan. In this study, the 10 particle-sizes from particle diameter 0.1 $\mu$m to a diameter of 10 $\mu$m were used.

## 6. Model Results

In order to validate the model calculations of the global transport of dust, we used the satellite estimates of absorbing aerosols (i.e., the aerosol index) that provide valuable information. Since the aerosol index is representative of the total amount

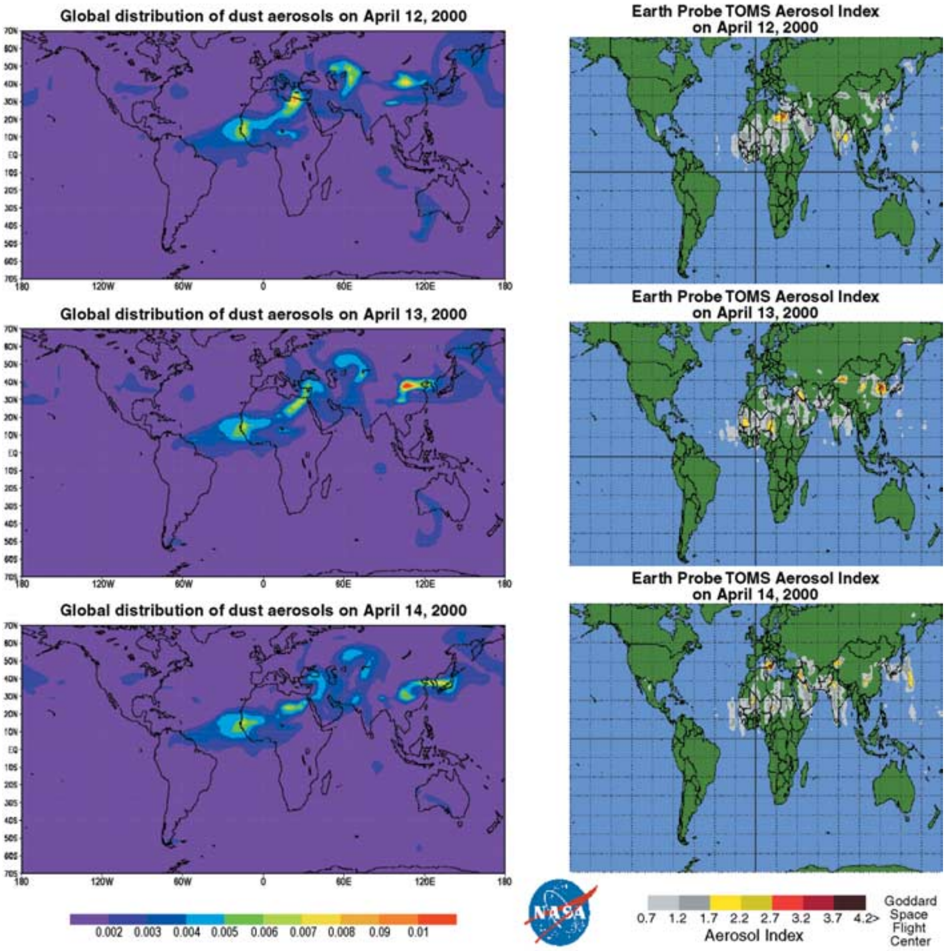


*Figure 1.* Comparisons of global distributions of the model calculated dust (left column) and the TOMS aerosol index (right column) during 12–14 April 2000.

of aerosols in the column, we compared the model results of the column dust mass with the satellite image of the TOMS aerosol index. The comparisons are presented in Figure 1 for 12–14 April 2000; the model results are taken at 00UTC for each day. In future studies, we will calculate the optical depth that corresponds to the aerosol index. It is clearly seen in Figure 1 that the dust storm that occurred in the Gobi Desert on 12 April, continued to develop more strongly on 13 April. The dust was transported and passed through the east coast of China to Korea and then Japan, and out to the Pacific Ocean. The model calculations are generally consistent with the TOMS observations.

The dust emissions from the dust storms that occur in China vary from location to location and from month to month. The primary dust sources in China originate from the Takla Makan Desert, the Gobi Desert, and the Loess region. The dust

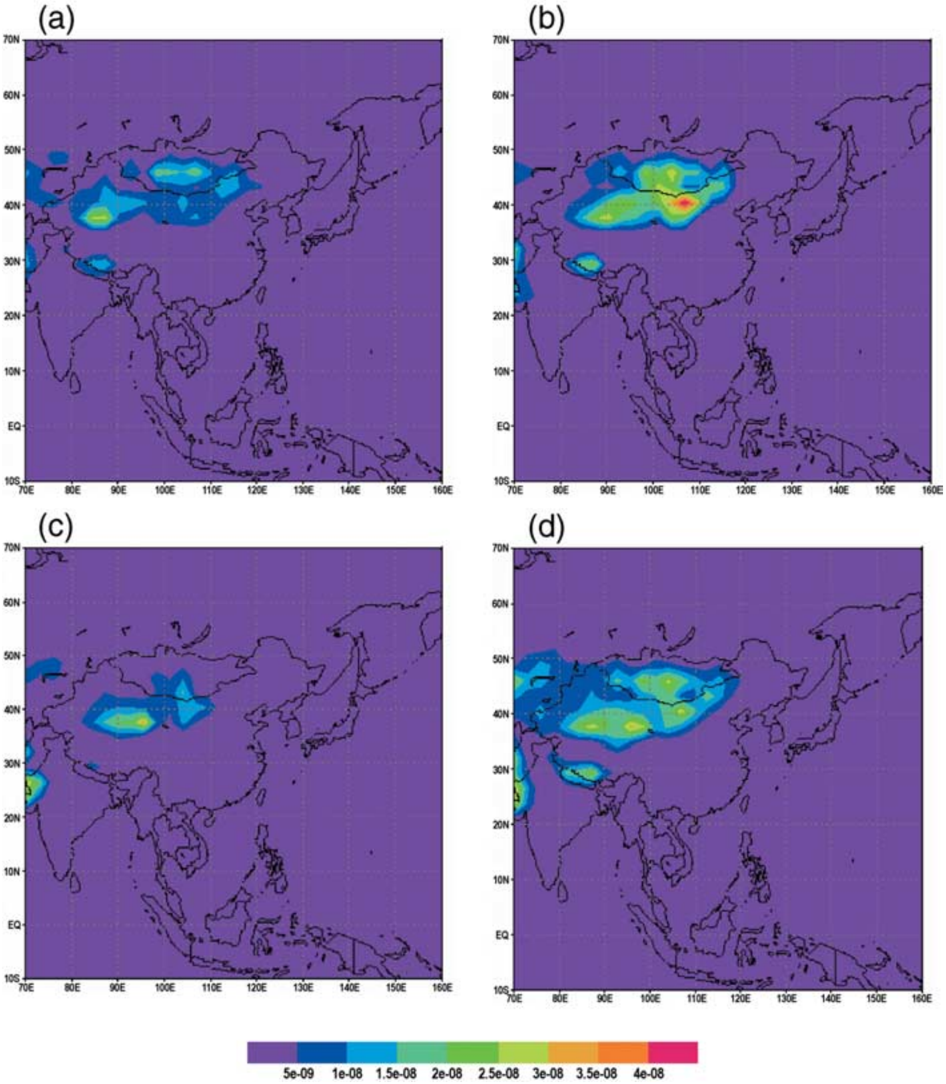


*Figure 2.* Model calculated mean dust emission rate (kg $m^{-2}$ $s^{-1}$) in the year 2000 for (a) March, (b) April, (c) May, and (d) annual.

storms usually occur from March to May because of low amounts of precipitation and strong winds associated with cold fronts during the springtime. Figure 2 shows the calculated monthly and annual mean dust emission rate for March, April, May, and the yearly average, respectively. Figure 2a indicates that the outbreak of dust occurred in March over the Takla Makan Desert. Figure 2b clearly shows that there was a major outbreak of dust associated with the Gobi dust storm that occurred from 12–14 April, as shown in Figure 1. A decrease in the dust emission can be seen in Figure 2c for May. The maximum of the annual mean dust emission rate in

Figure 2d is about 3e–8 kg $m^{-2}$ $s^{-1}$, and occurred east of the Takla Makan Desert. There are small dust emissions near the west of the Tibet region because the current input data for specifying surface conditions in the CTM do not classify the soil texture and the mountain ranges, such as the Himalaya. We are now revising the surface condition data to avoid these problems.

The integrated monthly and annual mean column dust masses in the air are shown in Figure 3 for March, April, May, and the yearly average, respectively. This figure shows that the dust mass in the air has a much stronger impact in April than other months for eastern China, Korea, and Japan. This re-suspended dust mass originated in the desert areas, primarily in the Gobi Desert and Loess region, and is then transported eastward and out to the Pacific Ocean. The impact of dust storms from the Takla Makan Desert to East Asia is generally smaller than that from the Gobi Desert and Loess region. In Figure 3d, the annual mean column dust mass over Korea and Japan is about 0.002 and 0.0017 kg $m^{-2}$, respectively.

In order to validate the model calculations, we can compare the model calculated total deposition of the dust mass with the measurements. Figure 4 shows the monthly total deposition for March, April and May, respectively. In this figure, it is seen that a significant deposition of dust and its impact fell over Japan in March and April, while in general it dramatically decreased in May. There are high amounts of dust deposition in the Tibet region. The simulations from other models have also shown moderately high aerosol optical depths in the Tibet region (e.g., Tegen and Fung, 1995). These high depositions are consistent with the model calculated maxima of the mean total deposition of $^{210}Pb$, which irreversibly attaches to submicron aerosols along regions of heavy precipitation activities and in monsoon areas (Lee and Feichter, 1995). However, based on the analyses of mineral aerosols by excluding the sulfate aerosols and other substances responsible for radiative forcing, the depositions are estimated to be small (Zhang *et al.*, 2001). Certainly, there needs to be more measurements in the Tibet region for validating the model simulations and comparisons. Here, the model calculations of total deposition are specifically compared with the measurements collected at three sampling stations in Japan, as shown in Figure 5. Figure 6 shows the comparisons of the model calculated monthly total deposition for the year 2000 with the measurements (g $m^{-2}$) taken at the MRI, Nagasaki and Yonaguni stations. It is seen that the model calculated monthly total depositions at the MRI station agree well with the measurements with a maximum deposition in April. This agreement indicates that the dust collected at MRI in the springtime is mainly contributed from the long-range transport of dusts from dust storms that occur in the desert areas in China. At the Yonaguni station that is located at the east of Taiwan in south Asia, the impact of the dust storms, as shown in the Figure 3d, is found to be minimal and consistent with the measurements in which the sea salt contribution was removed. At the Nagasaki station, the model underestimates the total deposition in March. This may be due to an underestimation of the precipitation at the station near the ocean. We

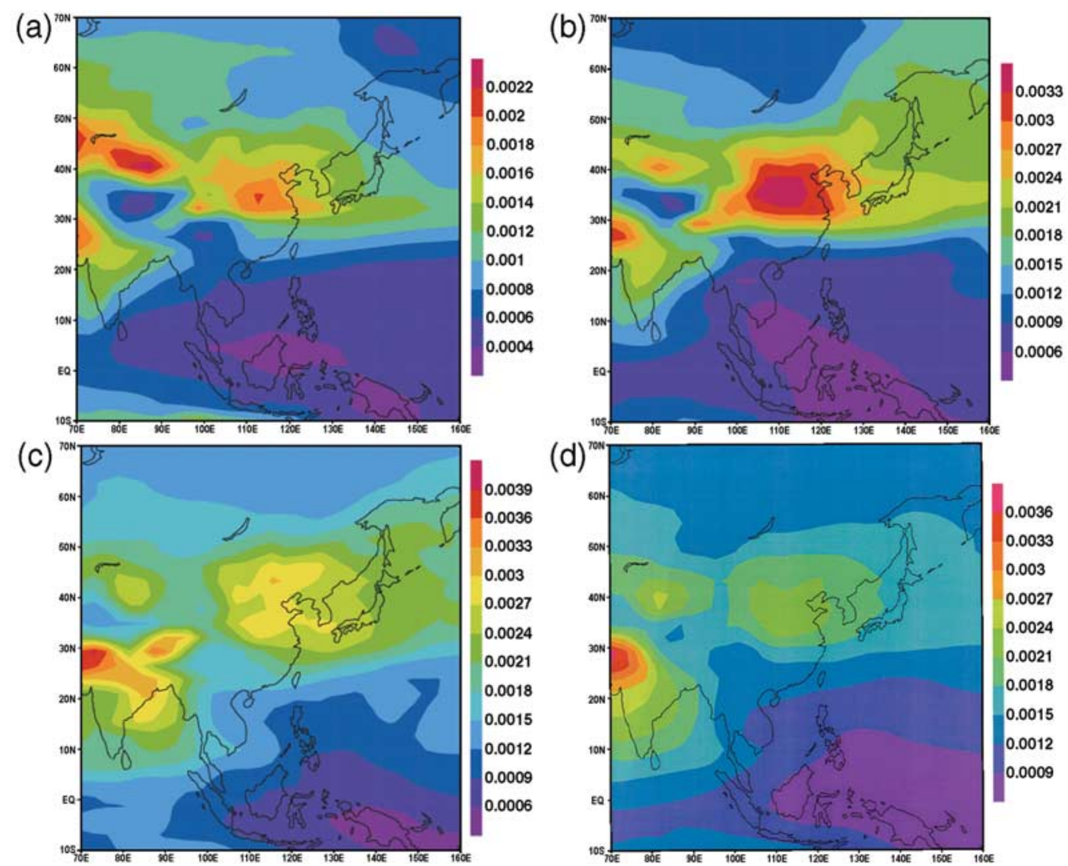


*Figure 3.* Model calculated mean column dust mass (kg $m^{-2}$ $s^{-1}$) in the year 2000 for (a) March, (b) April, (c) May, and (d) annual.

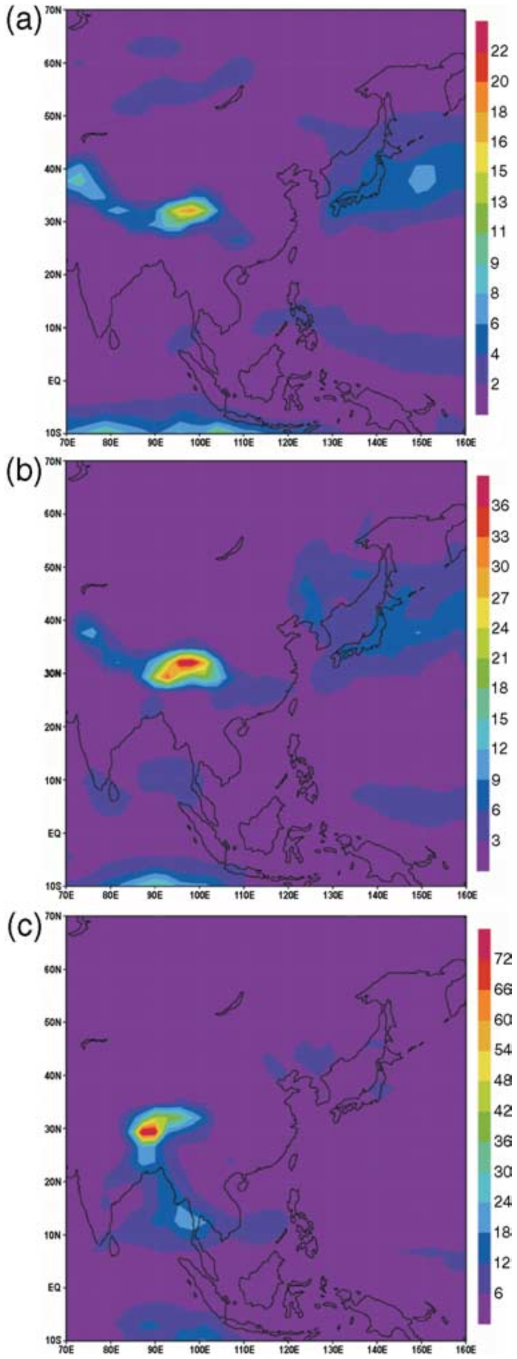


*Figure 4.* Model calculated total deposition of dust mass (g $m^{-2}$) in the year 2000 for (a) March, (b) April, and (c) May.

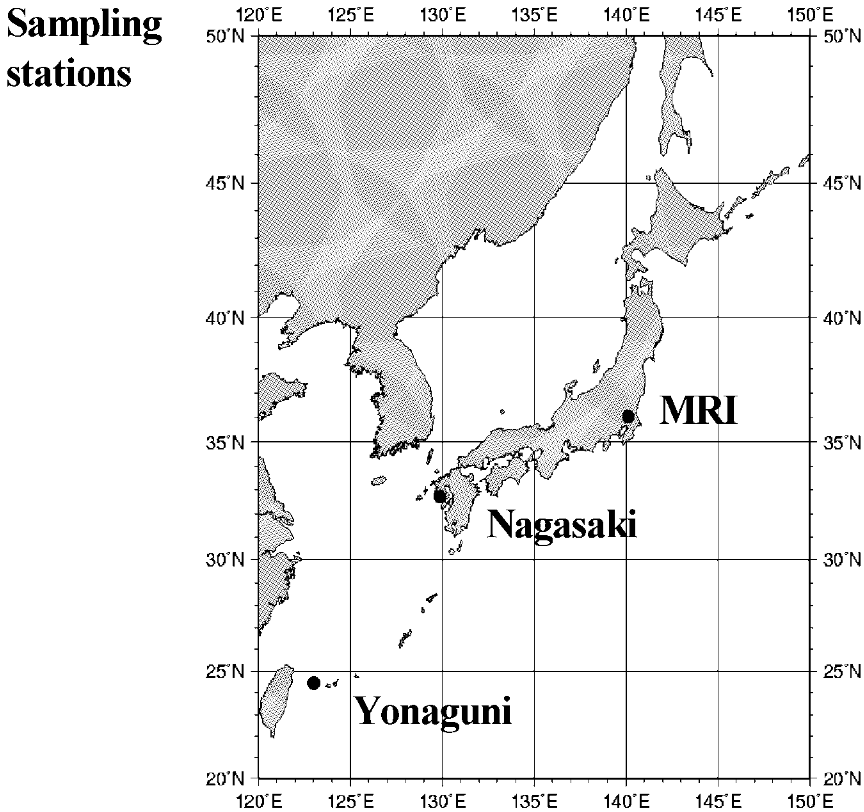


*Figure 5.* Locations of sampling stations for collecting the total deposition of dust mass in Japan.

are planning to collect more measurements at other sampling stations for detailed analyses and model comparisons.

## 7. Summary and Conclusions

We improved MRI's global chemical transport model by implementing a modified dust emission flux scheme and an improved atmospheric boundary layer for the calculations of the atmospheric eddy diffusivity in order to improve the model simulation of global dust transport. The model generally reproduced the temporal and spatial variations of dust reasonably well by comparing the model results with the TOMS satellite data. The detailed comparisons with the TOMS data will be continually pursued. The model also produced good agreement with measurements of the monthly total deposition of dust collected at three sampling stations in Japan.

For future studies, we will specifically examine the impact of dust storms that occur in each individual desert in East Asia. In addition, we will estimate the optical depths from the column mass loadings and directly compare them with the satellite

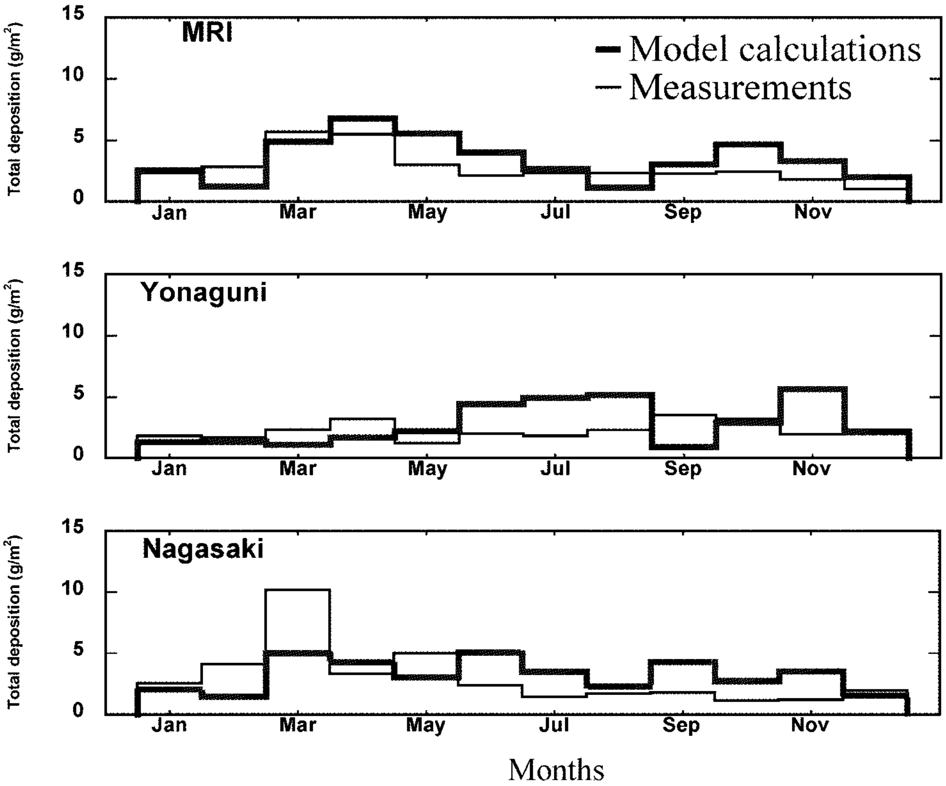


*Figure 6.* Comparisons of the model calculated monthly total deposition of dust mass (thick lines) with the measurements (thin lines) collected at MRI, Nagasaki and Yonaguni stations.

measured aerosol index. We will continue to validate the CTM by using radionuclide measurements, such as $^{222}Rn$ (radon) and its progeny, $^{210}Pb$ that can serve as useful tracers, and have been used for model validation by many atmospheric scientists (Rasch *et al.*, 2000; Lee and Feichter, 1995).

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