DOE Project: FG02-04ER63776

Emission, Dispersion, Transformation and Deposition of Asian Particulates over the Western Pacific Ocean: Part II

Final Technical Report

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DoE Award: Atmospheric Chemistry Program

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Abstract

In this project we developed and applied a coupled three-dimensional meteorology/chemistry/microphysics model to study the patterns of aerosol dispersion and deposition in the western Pacific area; carried out a series of detailed regional aerosol simulations to test the ability of models to treat emission, dispersion and removal processes prior to long-range transport; calculated and analyzed trajectories that originate in Asian dust source regions and reach the Pacific Basin; performed detailed simulations of regional and trans-Pacific transport, as well as the microphysical and chemical properties, of aerosols in the Asia-Pacific region to quantify processes that control the emission, dispersion and removal of particles; and assessed the contributions of regional-scale Asian particulate sources to the deposition of pollutants onto surface waters. The transport and deposition of aerosols and vapors were found to be strongly controlled by large and synoptic scale meteorology, convection, turbulence, and precipitation, as well as strong interactions between surface conditions and topographical features. The present analysis suggests that accurate representations of aerosol sources, transport and deposition can be obtained using a comprehensive modeling approach.

Summary of Research

During the course of this research, we performed detailed simulations of regional and trans-Pacific transport, as well as of the microphysical and chemical properties, of aerosols in the Asia-Pacific region to quantify processes that control the emission, dispersion and removal of particles. Our full microphysical calculations reveal that the modeled dust clouds closely correspond to those seen by the SeaWiFS satellite instrument. We also assessed the contributions of regional-scale Asian particulate sources to the deposition of pollutants onto surface waters in the western North Pacific Basin. The transport and deposition of aerosols and vapors were found to be strongly controlled by synoptic scale meteorology, convection, turbulence and precipitation, as well as strong interactions between surface conditions and topographical features.

As in previous work, the tools used in the present study include the Surface Meteorology and Ozone Generation (SMOG) integrated air pollution simulation system, and the fifth-generation of the NCAR/Penn State Mesoscale Model (MM5). The SMOG and MM5 models have been coupled to calculate aerosol transport and evolution throughout the Asia-Pacific region. We have specifically configured the MM5 for simulations in this area using a triple-nested grid ranging from the larger synoptic scale needed for regional weather and long-range transport simulations, to a local regional/urban resolution appropriate for emission/dispersion studies. The details of the models and applications can be found in previous project reports and in the literature.

Sources and composition of dust emissions

The main sources of dust from Asia are related to emissions from the Gobi Desert and the loess areas of northern and northwestern China. High winds regularly mobilize large quantities of surface material from these regions. While the largest particles fall to the surface near the source, finer particles are subject to long-range transport. These fine particles largely consist of crustal materials typical of eastern Asia arid zones. However, human activities and industrialization alter the dust composition significantly, especially when dust storms traverse the industrialized coastal regions of eastern Asia. To estimate the total dust burden to be expected from East Asia, the relative contributions of desert dust and anthropogenic emissions were

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characterized according to their elemental signatures. In previous work, the emissions were then scaled to measurements of aerosol composition.

Asia Dust Simulations and Trans-Pacific Transport

We simulated a major dust outbreak that originated in northern China in April 1998 (a snapshot for April 17 is shown in Figure 1). The dust source strength was defined using winds generated by the MM5 and an empirical surface suspension algorithm developed specifically for the region, as previously reported. The simulated development and transport of the resulting dust cloud (Figure 1a) was compared with the dispersing plume observed by the SeaWiFS instrument (Figure 1b). The detailed simulations of the dust source region, and subsequent early transport of the dust particles from the source region on April 15, are illustrated in Figure 5. Those trajectories indicate that the predictions of the early development of the clouds are consistent with the satellite images recorded during the event. Similarly, the full microphysical calculations shown in Figures 6 and 7 reveal that the modeled plumes correspond closely to the observations over several days of evolution. For example, both the model and satellite indicate a dense, tightly wound plume of dust covering the Yellow Sea on April 17, which would imply significant particle sedimentation over that region.

The simulations were extended for a longer period to characterize the trans-Pacific transport and deposition of the dust associated with this event. These results are illustrated in Figure 8. The simulations can again be compared to the observations taken from the SeaWiFS instrument (Husar et al., 2001) (Figure 9). The model accurately captures the timing and location of the dust clouds during this extended period. Indeed, the observations and simulations show that the dust plume remains quite dense over the western North Pacific Ocean, where deposition is consequently a significant factor. However, by the time the plume has reached North America, the dust concentration is substantially diluted, as the plume meanders along the jet stream track.

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a)

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Figure1. The transport of dust particles lifted by a storm that developed in western China and Mongolia on April 15, 1998. Top Panel: Model predictions at 00Z April 17, 1998. The dust plume is shown by red contours. Bottom panel: SeaWiFS satellite image at the same time (Husar et al., 2001).

(a)

(b)

(c)

Figure 2. Simulated evolution of the Asian dust cloud from April 19-25, 1998. The dust plumes are defined by red contours. These simulations can be compared to observations taken from the SeaWiFS instrument (shown in Figure 9). Panel (a) April 19; (b) April 22; and (c) April 25.

The present analysis suggests that accurate representations of aerosol sources, transport and deposition can be obtained using a comprehensive modeling approach. By implication, the radiative forcing associated with the simulated plumes should reasonably reflect the actual perturbations caused by similar dust outbreaks.

Figure 3. Locations of the dust event of April 17-25, 1998, as observed by the SeaWiFS satellite instrument (Husar et al., 2001).

Dust Deposition onto Western Pacific Waters

On regional scales, the transport and deposition of aerosols and vapors is strongly controlled by synoptic scale meteorology, convection, turbulence, and precipitation, as well as strong interactions between surface conditions and topographical features. The coupled modeling system developed for this study simulates the relevant dynamical processes, and couples them to microphysical and chemical processes as well. In this way, the types, size distributions and removal rates of the particles can be calculated in detail. In turn, the distributions and properties of aerosols can be used to determine deposition fluxes for various components, in addition to the regional-scale radiative impacts of the particles. This comprehensive approach—using a coupled three-dimensional meteorology/photochemistry/microphysics code—was initially applied to study the detailed patterns of aerosol dispersion over the western Pacific Ocean extending to North America, as described in previous sections of this report.

Using these dust dispersion simulations as a basis, we calculated the deposition fluxes of mineral dust onto the western Pacific. An example of the calculated fluxes is shown in Figure 12. Dust is raised by high surface winds from loose soils in the Gobi desert and the loess areas of eastern China, and transported by prevailing synoptic winds to the coastal region. Coarse particles with large fall velocities are deposited close to the source regions. Fine particles remain suspended for days, and are eventually carried over long distances by advection that is more zonal in nature. In the simulation illustrated in this report, fine dust was carried across the Pacific Ocean to North America. An important observation is that the strong convection associated with low-pressure systems, which causes the dust to be lifted in the first place, is also responsible for eventually lofting particles into the free troposphere where long-range transport occurs. Convective processes also enhance wet deposition and rainout rates, which brings dust from the middle troposphere to the surface, enhancing the deposition on the western Pacific Ocean within cyclonic depressions. Such enhanced deposition can be seen in Figure 12 near the Yellow Sea and southeast of Japan. Dust entrained into high-pressure systems, on the other hand, subsides more slowly as it moves downwind across the Pacific Ocean, leading to lighter deposition over

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much wider areas, including the North American continent. It is also apparent that Japan and Korea are directly along the path of typical Asian continental dust plumes, and experience significant impacts accordingly.

The present analysis suggests that accurate representations of aerosol sources, transport and deposition can be obtained through a comprehensive modeling approach. Indeed, the present study concludes that many of the key processes controlling aerosol evolution, dispersion and deposition can only be properly simulated using a sophisticated coupled approach. For example, the complex meteorological processing of dust from local and regional sources requires a multi-scale treatment of highly non-linear dynamical mechanisms. The determination of changes in particle size and composition that control the depositional and optical behavior of aerosols requires detailed microphysical modeling. Indeed, the complex composition of aerosols that are transported from rural through urban zones is the result of the interplay between emissions, chemical and microphysical transformations, and local to regional mixing regimes.

Figure 4. Predicted deposition fluxes of mineral dust (indicated by the red contours) for an event originating in the Gobi desert). The white vectors give surface winds. Terrain elevation is indicated by the background color gradient. High surface winds generated dense dust plumes that were subsequently transported to the western Pacific Ocean, leading to deposition on eastern China and the western Pacific. The largest deposition fluxes are correlated with the center of the low pressure system. Moreover, the closer to the source, the larger the particles deposited.

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Conclusion

We have developed and applied a coupled three-dimensional meteorology/chemistry/microphysics model to study regional-to-continental scale emission, dispersion, transformation and deposition of aerosols and other pollutants in eastern Asia and the northern Pacific Ocean Basin. Our modeling system integrates the MM5 meteorological code with the SMOG chemical tracer model. The coupled system treats the range of dynamical, microphysical, chemical and radiative processes thought to control the evolution of aerosols on the temporal and spatial scales of interest. The SMOG/MM5 modeling system utilizes a triple-nested grid to simulate the transport and evolution of photochemical pollutants and aerosols over large areas, such as the eastern Asia-western Pacific sector, while achieving regional resolution in specific locales, such as zones where dust originates in weather fronts. Simulations of the distributions and variations of particle types, sizes and compositions have been carried out for east Asia, and compared to observational data.

We find that aerosol and vapor dispersion and deposition are strongly dependent on the meteorological state of the atmosphere—as expected—but also on the surrounding topographical features, and the interactions between dynamics and landforms. Moreover, related localized processes, such as convection, turbulence and precipitation, strongly modulate the patterns of transport and deposition of gases and particles. On regional scales, aerosol emissions are distinctly partitioned between local deposition, regional boundary layer dispersion, and long-range advection in upper air layers. According to our analysis, aerosol-borne materials found on larger particles, including some trace metals, are mainly deposited locally, while materials concentrated on fine particles are deposited over regional-to-global scales through long-range transport. Each pollutant of interest has a distinct partitioning that depends on source characteristics as well as regional geographical features.

In eastern Asia, strong surface winds associated with the passage of frontal zones can generate large quantities of dust above dry areas, such as the Gobi desert. Dust scoured by these low-pressure systems can be lofted through strong convergence into the prevailing winds in the free troposphere, and subsequently advected over the Pacific Ocean as far as North America. Japan and Korea, which frequently lie directly along the path of such plumes, experience significant dust deposition as a result. Similarly, significant deposition occurs over the western Pacific Ocean, leading to biological implications owing to nutrients carried by the aerosol (e.g., McNair et al., 1998).

The present work indicates that accurate simulations of aerosol effects can be obtained using a comprehensive modeling approach. Further, many of the key processes require a sophisticated coupled modeling approach, including multi-scale treatments of transport and removal. Moreover, a detailed microphysical analysis that can resolve the complexity of particle evolution is essential.

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PUBLICATIONS RELEVANT TO THE PROJECT

Lu, R., R. P. Turco, K. Stolzenbach, S. K. Friedlander, C. Xiong, K. Schiff and G. Wang, "Dry deposition of airborne trace metals on the Los Angeles Basin and adjacent coastal waters," J. Geophys. Res., 108, 4074 (2003).

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