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张小曳　主编

气象出版社

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图书在版编目(CIP)数据

亚洲沙尘暴及其数值预报系统/张小曳编著. —北京:气象出版社,2006.10

ISBN 7-5029-4201-7

Ⅰ.亚… Ⅱ.张… Ⅲ.①沙暴-研究-亚洲 ②沙尘暴-数值天气预报-研究-亚洲 Ⅳ.P425.5

中国版本图书馆 CIP 数据核字(2006)第 117976 号

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出版发行:气象出版社

地　　址:北京海淀区中关村南大街 46 号　　**邮　　编**:100081

网　　址:http://cmp.cma.gov.cn　　**E-mail**:qxcbs@263.net

电　　话:总编室 010—68407112,发行部 010—62175952

责任编辑:郭彩丽　刘爱娣　胡育峰　　**终　　审**:黄润恒

封面设计:王　伟　　**责任技编**:都　平

责任校对:韩晓芳

印 刷 者:北京中新伟业印刷有限公司

开　　本:787×1092　1/16

印　　张:36.25　　**字　　数**:928 千字

版　　次:2006 年 11 月第 1 版　　**印　　次**:2006 年 11 月第 1 次印刷

定　　价:100.00 元

前　言

沙尘暴是一种自然现象，不仅对全球和区域的气候和生态系统有重要的影响，而且对工农业生产、交通、建筑设施、人民健康和生活等造成严重的危害。了解沙尘暴形成与发展变化的机制是国土沙漠化治理宏观决策的需要。准确地进行沙尘暴的预报和预警是我国防灾减灾和生态建设的需求。

沙尘气溶胶从干旱、半干旱区释放到大气之中，经传输和沉降形成了人们看到的沙尘暴过程。全球大气沙尘气溶胶约占大气颗粒物总量的一半以上，其源区主要分布于北半球的撒哈拉沙漠和包括中国北方沙漠在内的亚洲沙漠和沙地，以及南半球的澳大利亚沙漠。中国科学家的研究已经表明，主要起源于中国和蒙古国沙漠的亚洲沙尘是全球大气的重要组分，每年约向大气中注入 800 Tg 的沙尘粒子①。国际上的许多研究也证明，亚洲沙尘控制着北半球中纬度大气、黄土、深海沉积物中沙尘的总量。在没有人为扰动的地质历史时期，甚至可能控制着大气中的颗粒物总量。

沙尘暴的发生在我国黄土中的记录至少可以追溯到过去的 260 万年②。我国也有几百年的历史资料记录了"雨土"等沙尘暴现象的发生③。沙尘的极端输送事件——沙尘暴，作为亚洲最引人注目的环境现象之一，不仅对我国的生存环境造成影响，也影响到下风方的广大区域，成为北半球重要的国际环境问题之一，且一直是国际关注的研究课题。

当前国际全球变化研究特别重视对地气辐射平衡的扰动导致的气候变化的研究，且不论现代和地质历史时期的研究均有相当数量聚焦在沙尘气溶胶上。近一两年的研究显示，大气沙尘的变化是重要的气候驱动因子之一，且可能是地球气候系统 10～1 000 a 尺度快速变化的一个重要激发与响应因子，但模式估算其辐射强迫程度的不确定性较大，甚至其强迫的正负也没有确定(从＋0.5 W m^{-2} 到－0.7 W m^{-2})，间接效应的不确定性就更大。政府间气候变化专门委员会第三次评估报告④也特别提出了矿物(沙尘)气溶胶的气候重要性。

沙尘不仅气候效应显著，且已有证据表明，亚洲沙尘还通过控制输入海洋的风成铁等微量元素控制着海洋的生物产率，进而影响海洋对 CO_2 的吸收，间接地对气候产生影响。而气候的改变又会对亚洲沙尘的发生源区、释放量、输送过程、沉降量和形式产生反作用。沙尘在地球生物化学循环中的作用也是全球变化关注的热点之一。

认识沙尘与气候的相互作用，不仅应充分研究现今的沙尘，还应充分认识沙尘从过去到现在的变化过程，这不仅可将对沙尘发生规律的认识置于其自然演化的框架之中(这种演化

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① Zhang X Y, *et al*. 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *J. Geophys. Res.*, **102**: 28041－28047.

② Liu T S. 1985. *Loess and the Environment*. Ocean Press, Beijing.

③ Zhang D E. 1984. Synoptic-climatic studies of dust fall in China since the historic times. *Scientia Sinica*, **27**: 825－836.

④ IPCC. 2001. *Climate Change: The Scientific Basis*. Contribution of the Working Group I of Intergovernmental Panel on Climate Change to the Third Assessment Report. Cambridge Univ. Press, New York.

同土地荒漠化的自然循环也是密不可分的),还可以较准确地分离出现今人类活动(特别是土地利用)对沙尘暴的影响程度,为国土沙漠化治理的宏观决策提供科学的依据。

所有这些特别需要将分散的观测与数值模拟研究相结合,需要有通过观测验证的大范围模拟结果,需要将科学研究的成果转化为实际的亚洲沙尘暴数值预报系统,以减缓沙尘暴的影响。

在中国气象局气溶胶项目"涉及气候外交的关键气溶胶组分形成、变化机制及对气候的影响",科技部社会公益研究专项"建立我国新一代沙尘暴数值预报系统的方法和关键科学问题研究"(2004DIB3J115),国家重点基础研究发展规划项目"中国北方沙漠化过程及其治理研究"第3课题"沙尘暴形成机制及预报、预警方法"(G2000048703),中国科学院知识创新工程重要方向项目"亚洲沙尘形成、输送机制及其辐射强迫研究"(KZCX2—305),国家杰出青年科学基金项目"亚洲内陆沙尘与全球及区域气候、环境变化"(49825105)和国家自然科学基金面上项目"青藏高原对流层、中间层西风气溶胶特征与黄土堆积"(49673205)、"中国沙尘源区分布、搬运、沉积及所指示的古大气环流变迁"(49373188)、"西安地区大气气溶胶及现代降尘的化学组成及其与古沙尘对比"(48970256)等共同支持下,中国的亚洲沙尘暴研究团队对沙尘暴进行了大量的观测、数值模拟与分析工作。主要采用了大规模、细致的观测与数值模拟相结合的研究方法,不仅瞄准基础科学研究,也注重将科学研究的成果向应用系统转化。在亚洲沙尘暴的潜在源区(中国沙漠及其邻区)和下风沉降区,开展了大气气溶胶粒子的理化、辐射特性的空中与地面相结合的立体观测,获得了点—线—面相匹配的空间及时间序列观测结果,比较详细和系统地了解亚洲沙尘暴的物理特征和化学组成、变化历史、源地、释放量、输送和沉降的方式以及它们与天气、气候变化的关系;另一方面,在大量观测数据的输入和验证的基础上,建立了可定量描述出亚洲沙尘暴释放、输送与沉降的数值模拟系统,并开展了沙尘气溶胶气候效应的研究。在沙尘暴起沙、输送、沉降等机制研究和数值模拟的基础上,将亚洲沙尘暴模式与中尺度气象模式MM5在线耦合,并与中国新一代数值天气预报模式GRAPES在线耦合,在源区起沙数据库系统和中国气象局地面与卫星观测等数值同化系统的支持下,建立了亚洲沙尘暴数值预报系统。

团队1990年就开始了沙尘气溶胶的研究工作,2001以来更是大规模地进行研究,观测网络与数值模拟紧密结合,并在地质历史时期的沙尘暴研究中做了大量的工作。除了获得迄今国际上在亚洲沙尘暴主要源区和关键沉降区较为系统,且对亚洲沙尘研究至关重要的一些关键资料外,还在沙尘暴的源区、输送路径、高度、释放和沉降收支,以及形成的主要控制因素等方面取得了明显进展。研究结果已有180篇论文发表。其中53篇发表在*Journal of Geophysics Research*, *Journal of Atmospheric Chemistry*, *Atmospheric Environment*, *Geophysics Research Letters* 和*EPSL* 等高影响因子国际期刊上,EI论文8篇,国内核心期刊论文108篇,其他论文11篇。截至2006年9月,发表在SCI期刊上的文章被引用643次,在沙尘暴研究的一些关键科学问题上的研究结果获得国内外同行的承认。国际大型研究计划ACE-Asia的*Journal of Geophysics Research* 专集也有1/3的文章引用了本项研究成果主要完成人一篇或数篇相关文章。中国科学家由于在沙尘暴领域的出色工作而主导了世界天气研究计划(WWRP)中的国际沙尘暴项目(SDS)。正在编写的政府间气候变化专门委员会(IPCC)第四次评估报告中,引用了亚洲沙尘暴源区分布、气候因素较沙漠化因素对亚洲沙尘暴有更重要作用,以及沙尘导致海陆热力差异快速改变进而影响季风气候系统

快速变化等有关成果。在取得科学研究进展的同时，中国气象局大气成分观测与服务中心在与国家气象中心、国家卫星气象中心和国家气象信息中心等单位的密切合作下，建立了亚洲沙尘暴的数值预报系统，并在中国气象局成功运行，取得了良好的数值预报效果。

本项研究取得的主要研究结果如下：

(1) 获得并完善了亚洲沙尘暴关键区域(中国沙漠、黄土高原、青藏高原、中国东北部沙地、中国沿海)大气沙尘气溶胶理化特征和光学特征数据集。

(2) 揭示了亚洲沙尘暴的10个主要源区的分布。

(3) 首次定量估算出亚洲沙尘的总排放量。

(4) 获得了亚洲沙尘暴影响我国特别是北京的5条主要的输送路径，以及在不同区域最大浓度所处的高度及跨洋输送路径。

(5) 首次提出了亚洲沙尘区域—全球尺度、冰期—间冰期输送的概念模型。

(6) 辨识出亚洲沙尘在接近源区和远离源区沉降的控制过程，以及沙尘在黄土高原沉降后的再改造份额。

(7) 了解了亚洲沙尘在各主要源区和沉降区的“收支”状况。

(8) 获得了沙尘记录的长时间尺度大气环流变化序列及信息。

(9) 认识了亚洲沙尘气溶胶的主要辐射特征。

(10) 提出了沙尘气溶胶增强、减弱导致的海陆热力差异快速变化激发并调制着东亚冬季风系统快速变化的观点。

(11) 首次指出天气、气候因素而非土地荒漠化因素是控制亚洲和我国沙尘暴发生的主导因素的观点，并提出了明确的科学依据。

(12) 获得了亚洲沙尘暴的不同尺度的时间变化序列，开发了卫星定量遥感反演沙尘暴特征量的方法，提取出影响亚洲沙尘暴的关键天气、气候因子。

(13) 建立了国际先进水平的沙尘暴数值预报系统，并投入实际运行，取得了较好的效果。

为了较集中地表达研究团队有关亚洲沙尘暴的研究结果，并与国内外相关领域的研究人员和高校师生进行学术交流，我们从项目资助的已经发表的论文中选择了37篇，编撰成本论文集，代表了亚洲沙尘暴研究几个不同方面的主要研究结果。论文集分为六部分，分别是：一、亚洲沙尘气溶胶的物理特性与化学组成；二、亚洲沙尘暴的源区分布、释放量及成因；三、形成沙尘暴的天气、气候特征分析；四、沙尘暴的数值模拟与预报；五、沙尘的气候效应；六、地质历史时期的亚洲沙尘暴。同时在附录中列出了有关亚洲沙尘暴研究项目已经出版的其他论文的目录。

气象出版社的郭彩丽副编审为本文集的顺利出版付出了巨大的努力，在此致以诚挚的谢意。

希望本文集的出版有助于亚洲沙尘暴相关研究的交流，并为沙尘暴预报、预警、治理提供一定的科学基础。

张小曳

2006年8月

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第一部分

亚洲沙尘气溶胶的物理特性与化学组成

Study on Three Dust Storms in China

—Source Characterization of atmospheric Trace Element and Transport Process of Mineral Aerosol Particles[①②]

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Key Words—dust storm; aerosol; trace elements; China

1. Methods

All of the aerosol samples were collected in the spring of 1990 during and after three dust storms. The first was on April 6 in Xi'an (34.3°N, 108.9°E) (dust storm I); the second was in Shapotou (37.5°N, 105°E) and Beijing (39.9°N, 116.4°E) on April 10 and in Xi'an on April 11 (dust storm II); and the third on April 25 in Beijing (dust storm III). Shapotou is near the southern edge of the Tengger Desert and this site is considered more or less representative of a desert region. The singie-orifice 8-stage cascade impactors [Proton Induced X-ray Emission (PIXE) International Corporation, Tallahassee, Florida] were used for sampling. The flow rates were approximately 1 L min^{-1}, thus providing eight particle fractions with the following nominal ranges of particle size, expressed as aerodynamic diameters:

stage 0<0.25 μm, stage 1=0.25 to 0.5 μm, stage 2=0.5 to 1 μm,
stage 3=1 to 2 μm, stage 4=2 to 4 μm, stage 5=4 to 8 μm,
stage 6=8 to 16 μm, stage 7>16 μm.

The sampling height was 8 to 10 m and the sampling duration was usually 3—5 hours per day.

The PIXE analyses were performed using the 2.5 MeV protons with a 50 nA beam current produced by 1.7×2 MV tandem accelerator at Beijing Normal University. Using these procedures we were able to determine the concentrations of 21 elements: Al, As, Br, Ca, Cl, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, S, Se, Si, Sr, Ti, V, and Zn. The data were corrected for

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① 原载 *Chinese Science Bulletin*, **37**(11): 940—945, 1992.

② Project supported by the National Natural Science Foundation of China and the National Science Foundation of the United States.

backgrounds for the coated filters.

We combined the concentrations of stage 7 with stage 6 and designated the sum as stage 6. We did the same for stages 0 and 1 and designated the combination as stage 1.

For quality control/quality assurance (QC/QA), the concentrations of seven main elements (Al, Ca, Fe, K, Mn, Si, and Ti) were determined in five aliquots of two different samples. Similar-comparisons were made for two aliquots of a standard reference material (Geochemical standard reference sample No. 8, National Bureau of Chemical Exploration Analysis, 1984[1]). The QC/QA tests showed that (1) there were no significant differences between the replicate analyses of two samples and (2) the analysis for K, Ca, Ti, Fe, Al and Si were within 20% of the standards; Mn was within 50% of the standard.

2. Results and Discussion

2.1 The Chemical Composition of Aerosol Particles and the Mass-Particle Size Distributions (MSDs) of Trace Elements

The concentrations of trace elements in the aerosol samples from Shapotou, Xi'an and Beijing which include samples collected both during and after dust storms showed that the highest concentrations of Al and the other crustally derived elements were observed at Shapotou in the morning of April 10, 1990. During that dust storm, the Al concentration reached 82 $\mu g\ m^{-3}$; this is equivalent to a mineral aerosol concentration of $\sim$1 $mg\ m^{-3}$, because mineral aerosol is approximately 8% Al by weight[2]. The concentration of Al in Shapotou dropped dramatically (by almost 90%) in the sample collected later on the same day. In Xi'an and Beijing, the highest atmospheric Al concentrations were 48 and 20 $\mu g\ m^{-3}$, respectively, while the corresponding lowest concentrations were 10 and 1.6 $\mu g\ m^{-3}$, respectively.

Enrichment factors were calculated based on the crustal reference data of Taylor[2]. Enrichment factors related to crustal source are defined as: $EF_{crust} = (X/Al)_{air}/(X/Al)_{crust}$, where X, Al are expressed in concentrations (e.g. $\mu g\ m^{-3}$), and these calculations support the hypothesis that mineral particles, which most likely originated from the desert and gobi regions of northern and northwestern China, dominate the concentrations of many elements. One group of eleven elements (Al, Ca, Cr, Fe, K, Mg, Mn, Si, Sr, Ti, and V) generally exhibited relative proportions in the aerosol particle samples similar to those in average crustal material. Of these, the EF_{crust} values for Fe, Mg, Si, Sr, and Ti were less than 5 for all stages of the cascade impactor sample collected in Shapotou during dust storm II. The EF_{crust} values for a second group of elements (As, Br, Cl, Co, Cu, Ni, Pb, S, Se and Zn) in Shapotou, however, indicated that these elements were increased in content relative to crustal sources even during the dust storms.

We compared the data for a cascade impactor sample collected during dust storm II in Shapotou on April 10 with a sample from the same dust storm collected in Xi'an on April 11 and with a sample obtained after dust storm II. Many of the elements, including several that normally get more abundant relative to crustal rock, exhibited similar MSDs in the sample collected during dust

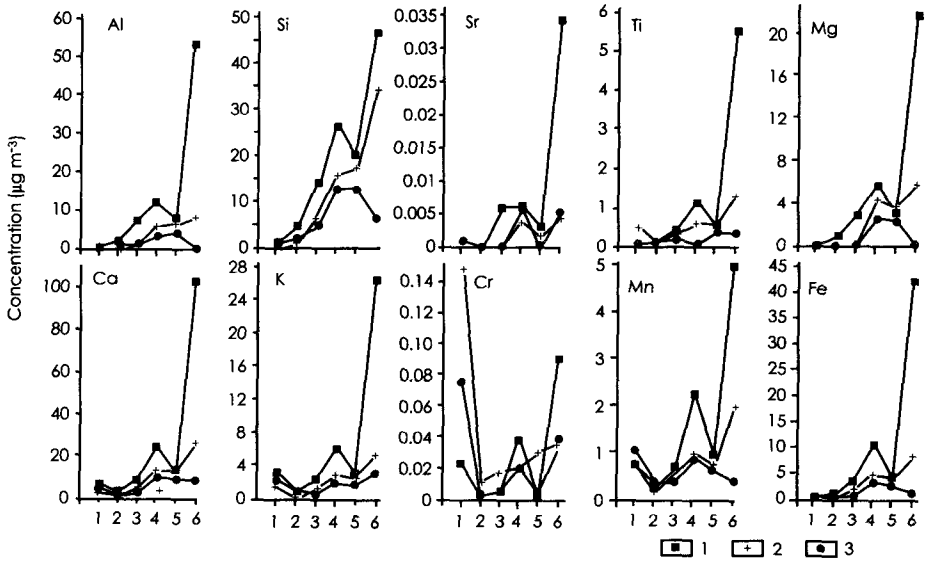

Fig. 1. Mass size distributions for crustally-derived trace elements in Shapotou and Xi'an during and after dust storm II. 1. Shapotou sample of dust storm II; 2. Xi'an sample of dust storm II; 3. Xi'an sample after the dust storm. Mass diameter range for the cascade impactor: stage $1<0.5$ μm, stage $2=0.5-1$ μm, stage $3=1-2$ μm, stage $4=2-4$ μm, stage $5=4-8$ μm, stage $6>8$ μm.

storm II in Shapotou (Fig. 1). More than one-third of the mass of the crustally derived elements occurred on the 6th stage of the cascade impactor (i. e. the largest praticles), and approximately 80% to 90% of their total mass was on the degree of particles larger than 2 μm aerodynamic equivalent diameter (stages 4 through 6). The concentrations of the crustal elements increased with the size of the particles, with an especially sharp increase evident for the 4th stage of the impactor.

2.2 Changes in Aerosol Composition during Dust Storm II

The enrichment factors for several of the crustally derived elements (Fe, K, Mg, Mn, Si, Ti, and V) in the Xi'an samples from dust storm II were more than 30% higher than in Shapotou samples from the same dust storm. This is because the concentration of Al decreased more rapidly as the storm passed from Shapotou to Xi'an than those of the other crustal elements. Although the differences are small, we consider it quite possible for the mineral aerosol to be fractionated during the ~380 km of transport from Shapotou to Xi'an. Previous studies by Johnson (1976)[3] suggest that the selective removal of aerosol particles by size leads to mineral sorting and hence chemical difference in atmospheric vs. dust fall samples. Changes in the enrichment factors also could be explained if the samples from Xi'an were influenced by a local source of dust or other particulate material that was relatively depleted in Al.

A comparison of the cascade impactor data for the trace elements in the samples collected during dust storm II shows that MSDs of several crustal elements (Al, Fe, Mg, Si, Sr, and Ti)

exhibited similar changes as the dust storm passed from Shapotou to Xi'an. In Xi'an the concentrations of these elements on each of the cascade impactor filters tended to be lower than those in the samples from the desert region. More importantly, the greatest difference between the Shapotou and Xi'an samples occurred in the largest particle fraction (i. e. stage 6), indicating that during atmospheric transport over the relatively short distance from the desert region to the southern margin of the Loess Plateau of China, some of the mineral aerosol particles were sorted as a function of size. As the sorting evidently was the most important for the largest particles, it is possible that the effects of the sorting become less significant as transport proceeds. In fact, MSDs of the trace elements in the samples collected after the dust storm in Xi'an were qualitatively similar to those of marine samples described by Duce[4]. These results demonstrate that MSDs of trace elements provide some insight into the sources for aerosol particles but that the sorting of particles during the initial phase of transport also influences MSDs.

2.3 The Sources for the Mineral Aerosol Particles during the Three dust Storms

During the three dust storms, MSDs of crustally-derived elements (Al, Ca, Fe, K, Mg, Mn, Si, Sr, and Ti) were generally similar. This was true not only for the samples from the desert region near Shapotou but also for those from Xi'an and Beijing. However, a comparison of samples from Shapotou and Xi'an showed that the ratios of several elements (Mg/Ti, Al/Fe, Mg/K) decreased after the dust storms subsided for reasons not yet understood, but possibly related to fractionation of the mineral aerosol discussed above.

A consideration of the data presented in Table 1 shows that changes in elemental ratios could occur as a result of particle sorting. The primary assumption for this simulation is that during transport, the largest particles are removed more rapidly than smaller particles, and theory

Table 1. Ratios of Mg/Ti, Al/Fe, and Mg/K in Aerosol Particles and Soils from China

Site (Date, 1990)	Dust Storm (During/After)[a]	Mg/Ti	Al/Fe	Mg/K
Xi'an (April 6)	I (During)	4.40	1.11	0.83
Xi'an (April 7)	I (After)	3.13	1.00	0.61
Shapotou (April 10, AM)	II (During)	4.36	1.29	0.81
Shapotou (April 10, PM)	II (After)	3.38	1.10	0.77
Beijing (April 10, AM)	II (During)	3.76	0.85	0.83
Beijing (April 10, PM)	II (After)	2.77	0.64	0.68
Xi'an (April 11, AM)	II (During)	4.07	1.03	1.00
Xi'an (April 11, PM)	II (After)	3.30	1.37	0.68
Beijing (April 25)	III (During)	2.78		0.65
Site	**Reference**	**Mg/Ti**	**Al/Fe**	**Mg/K**
Xinjiang, China	Wen 1989[5]	4.91	1.23	1.05
Inner Mongolia, China	GSS 1984[1]	2.31	2.17	0.29
Song-Liao Plain, China	Wu *et al*. 1986[6]	1.26		

a) During or after the dust storm.

indicates that the removal of the largest particles larger than 1 μm in aerodynamic diameter would cause the Mg/Ti ratio to decrease by roughly 70%, the Al/Fe ratio to decrease by 20%, the Mg/K ratio to decrease by roughly 30%.

Further analyses of the elemental ratios show that they differed between dust storms I and II vs. dust storm III. The ratios for dust storms I and II were consistent with the data for Xinjiang, while the ratios for dust storm III were typical of a source in Inner Mongolia (Table 1). This preliminary analysis indicates that elemental ratios may vary among source regions. Furthermore, the analysis of elemental ratios may be useful for future studies of the relationships between source soils and aerosol particles. Meteorological analyses and evidence from satellite images of dust storms support the conclusions drawn from the chemical data.

3. Conclusion

During dust storms in China the concentrations of a suite of eleven crustal elements in aerosol particles were much higher than normal, but the concentrations of these elements decreased rapidly after the storms abated. This marked short-term variability in dust concentrations apparently is characteristic of the transport of mineral aerosol particles near the source regions in northern and northwestern China. Among the crustally-derived elements, Al, Fe, Mg, Sr, Si, and Ti were most strongly affected by the crustal source, and they can be considered as key elements for studying the atmospheric transport process of mineral particles. MSDs of the crustally-derived elements exhibited changes that evidently were associated with particle sorting, and thus MSDs may provide unique information relative to the atmospheric transport of soils. Elemental ratios, especially Mg/Ti, Al/Fe and Mg/K, may be useful for investigating the sources for aerosol particles.

Acknowledgments—We express our gratitude to the staff of the short-term weather forecast group of Shaanxi Province Meteorology Bureau and to the Institute of Desert Research, Academia Sinica, Lanzhou, for the meteorological and logistical support. Li Chang'an and Li Zhaoyuan helped to interpret the meteorological data. Wu Xihao, Wang Mingxing, Chen Mingyang and Wei Lanying improved the manuscript through their comments and suggestions.

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