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Multi-Source Characteristics of Atmospheric Deposition in Nanjing, China, as Controlled by East Asia Monsoons and Urban Activities

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ABSTRACT

Atmospheric deposition, a major pathway of metals entering into soils, plays an important role in soil environment, especially in urban regions where a large amount of pollutants are emitted into atmosphere through various sources. In order to understand the characteristics of atmospheric deposition in urban area and its relation with natural and anthropogenic sources, a three-year study of atmospheric deposition at three typical sites, industrial zone (IN), urban residential area (RZ) and suburban forested scenic area (FA), was carried out in Nanjing, a metropolitan city in eastern China from 2005 to 2007. The bulk deposition rate and element composition of atmospheric deposition varied spatio-temporally in the urban zones of Nanjing. The concentrations of Cu, Zn, Pb and Ca in the atmospheric deposits were strongly enriched in the whole Nanjing region; however, anthropogenic pollutants in atmospheric deposits were diluted by the input of external mineral dust transported from northwestern China. Source apportionment through principal component analysis (PCA) showed that the background atmospheric deposition at the FA site was the combination of external aerosol and local emission sources. The input of long-range transported Asian dust had an important influence on the urban background deposition, especially in spring when the continental dust from the northwestern China prevailed. Marine aerosol source was observed in summer and autumn, the seasons dominated by summer monsoon in Nanjing. In contrast, the contribution of local anthropogenic emission source was constant regardless of seasons. At the RZ and IN sites, the atmospheric deposition was more significantly affected by the nearby human activities than at the FA site. In addition, different urban activities and both the winter and summer Asian monsoons had substantial impacts on the characteristics of dust deposition in urban Nanjing.

Key Words: aerosol, anthropogenic pollutants, Asian dust, metals, source apportionment, urban environment

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INTRODUCTION

Atmospheric deposition is considered to be the major pathway by which substances from the atmosphere enter the earth surface ecosystems. The inputs of nutrients such as S, N and Fe (Bishop *et al*., 2002; Okin *et al*., 2011) and base cations such as K, Na, Ca and Mg from the atmosphere have a positive effect, either directly or indirectly, on the receiving ecosystem. However, excessive inputs of SO_4^{2-}, NO_3^- or NH_4^+ could contribute to the acidification and eutrophication of ecosystems (Troost *et al*., 2012). Furthermore, toxic metals, such as Cu, Zn, Pb and Cr, could cause significant damages or risks to the environment and human health (Sharma *et al*., 2008). Previous studies across various regions of the world showed that dust deposition affects substantially the properties, especially the enrichment of heavy metals, of surface soils (Hernandez *et al*., 2003; Porder *et al*., 2007; Hovmand *et al*., 2008; Bermudez *et al*., 2012). Understanding the sources and controlling factors of atmospheric deposition is essential for the assessment of regional soil and environmental quality.

In general, natural mineral dust and sea salt are the main sources of global aerosols, with an estimated production rate of 3.062×10^9 Mg year^{-1}, while anthropogenic aerosols are produced at an estimated rate of 3.8×10^8 Mg year^{-1} (Hewitt and Jackson, 2003). In urban regions, large amounts of anthropogenic pollutants enter the atmosphere from both stationary sources (power plants, industries and residential heating) and diffuse sources (road traffic) (Bilos *et al*., 2001). As a result, the average concentrations of trace metals in urban environments are generally 5–10 times higher than those in rural environments and 100 times higher than those in remote areas (Nriagu, 1990; Seinfeld and Pa-

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ndis, 1998).

In numerous studies, environmental indicators, such as mosses (Wolterbeek, 2002), peat bogs (Shotyk *et al.*, 2002), ice cores, lake sediments and soils, have been used to archive the deposition history indirectly. On the other hand, high (low)-volume air samplers or passive bulk deposition samplers have been commonly used for the direct research of pollutants in aerosols and atmospheric deposits (Galloway *et al.*, 1982; Wu *et al.*, 2007). In contrast to high (low)-volume air samplers, passive bulk deposition samplers are controlled solely by the ambient environment and can provide valuable information on the fluxes of atmospheric metal deposition and other pollutants to the surface environment (Wong *et al.*, 2003). Receptor modeling methods such as principal component analysis (PCA), positive matrix factorization (PMF) and chemical mass balance (CMB) (Viana *et al.*, 2008), based on the chemical characteristics of atmospheric deposit samples, have been developed to identify the sources of pollutants.

In China, rapid economic growth in the last thirty years has strongly stimulated the formation of large urban conglomerates and caused serious air pollution problems in many regions, such as the Beijing-Tianjin region, the Yangtze River delta (YRD) region and the Pearl River delta (PRD) region (Chan and Yao, 2008). As one of the large cities in the YRD region, Nanjing has seen rapid urban expansion and fast increase of urban inhabitants as well as development of large scale chemical and manufacture industries. The local emission sources including industrial, traffic and residential ones are supposed to be added upon long-range sources especially the transportation by the winter and summer monsoons. On the other hand, as northwestern China and southern Mongolia are one of the main source regions of global mineral dust (Sun *et al.*, 2001), approximately 8×10^8 Mg year^{-1} of mineral dust is produced from the Taklimakan Desert, the loess region and the arid Gobi Desert (Zhang *et al.*, 1997) and transported eastward to eastern and southeastern China, Korea, Japan and the Pacific Ocean, and even to North America (Jaffe *et al.*, 2003; Shao *et al.*, 2011), consequently increasing the amounts of particle matter (PM) and altering the composition of atmospheric deposition in these downwind regions (Han *et al.*, 2007; Kim *et al.*, 2008).

To characterize the deposited dust and to trace its sources of different seasons in Nanjing may not only illustrate the input amount of extraneous environmentally sensitive materials such as heavy metals and other pollutants to local soil environment, but also distinguish the contribution of local and long-range sources of deposited materials. In the present study, atmospheric deposition was monitored in Nanjing, which is located on the southern border of this dust-affected region in China. The main objectives of the study were: 1) to analyze the characteristics of urban background atmospheric deposition; 2) to compare the contribution of local human activities to atmospheric deposition in different urban areas and 3) to identify the main sources of atmospheric deposition in different urban areas. This study aimed to provide a better understanding for the sources and fluxes of air pollutants in this typical city and may help to improve environmental management and policy making for air and soil quality control countermeasures.

MATERIALS AND METHODS

Description of the study area

Nanjing City, located in the west of the YRD region in eastern China (31°14′–32°37′ N, 118°22′–119°14′ E, 7–10 m above sea level) and about 300 km away from the East China Sea, is one of the most developed regions in China. The administrative zone of Nanjing has an area of 4 844 km^2 and a population of 8.12 million. This city lies on the plain formed by sediments from the Yangtze River and the Qinhuai River. There are some scattered low hills around this city, occupying 64.5% of the city's area. Most of the hills are lower than 200 m except for the Purple Mountain (446 m), which is located in the city's eastern suburb (Fig. 1). The study area has a subtropical humid monsoon climate, and the wind direction reverses seasonally. In winter and spring (from December to May), as dominated by northwest wind and weak cold high pressure, the weather in Nanjing is cold and dry. During this period, the area is likely to undergo heavy atmospheric pollution. In summer and autumn (from June to November), the prevailing wind is from the Pacific Ocean, with humid and warm weather conditions. More than 70% of the annual precipitation occurs during this period, and it would be up to 50% in summer season. The central part of Nanjing is mainly used for commercial and residential purposes. The industrial zones are located in the southeast suburban area, the northeast urban area and on the north bank of the Yangtze River. The main industries of Nanjing include electronics, steel manufacture, petrifaction and motor manufacture.

Sampling and analysis

Passive bulk deposition samplers were set at three typical sites, industrial zone (IN), urban residential area (RZ) and suburban forested scenic area (FA), re-