Seasonal characteristics of particulate matter in Osaka

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Abstract

Particulate matter (PM) is sampled widely worldwide because high PM concentrations can degrade air quality. Our group monitors PM in Osaka, the second largest metropolitan area in Japan. Because of industrial plants and highways located near our observation site, a clear atmosphere is rare in this area. The air is usually polluted with suspended particles emitted from vehicles and industries. In this study, seasonal PM variation in Osaka using ground observation and model simulation is investigated. Results showed that PM concentrations were highest during spring and summer because of dust events in spring and photochemical reactions in summer. As such, the influence of anthropogenic PM at this site is significant during summer.

1. Introduction

Air pollution in megacities has become a serious problem. In particular, fine particles called $PM_{2.5}$, whose diameter is 2.5 μm or less, are problematic. Particulate matter (PM) pollution characterized by high $PM_{2.5}$ readings cause a spike in the mortality rate of patients suffering from heart and lung diseases. Because fine particles are much smaller than inhalable coarse particles, they penetrate deeper into the lungs and more severely affect human health. Anthropogenic sources of $PM_{2.5}$ include automobiles, factories, coal-burning power plants, and heaters in homes. In addition, dust particle size decreases as the particles are transported via westerly winds over long distances; therefore, dust storms may contain high concentrations of fine particles [1]. Accordingly, $PM_{2.5}$ concentration levels correspond with those of both anthropogenic and natural aerosols.

Osaka is the central city in the second largest metropolitan area in Japan. The greater Osaka metropolitan area covers 7,800 square kilometers within a radius of 50–60 km from the center of Osaka. The population exceeds 17 million, making it one of the world's biggest metropolitan areas. Our observation site is located in eastern Osaka, as shown in Fig. 1. The area is known for its manufacturing technologies by small- and medium-sized enterprises. This area rarely experiences clear atmospheric conditions with a limited number of small particles and often suffers high levels of pollution from particles emitted from diesel vehicles and industrial activities [2].

PM levels in Osaka are monitored with a PM sampler (SPM-613D, Kimoto Electric, Japan) [3], installed at the aerosol robotics network (AERONET) site on the roof of a building at Kinki University. Worldwide, National Aeronautics and Space Administration (NASA)/AERONET data are primarily available as ground-based sun-photometric products that provide measurements of the aerosol optical thickness (AOT) and the Ångström exponent (α) [4, 5]. Furthermore, at the same site, a standard light detection and ranging (LIDAR) instrument, which is part of the national institute for environmental studies (NIES)/LIDAR network [6], has been set up.

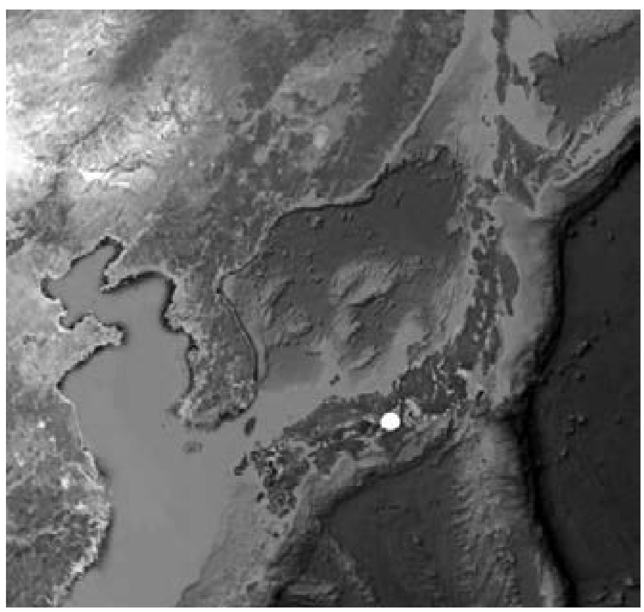

Fig. 1. Map of the observation site, located at 135.59° E, 34.65° N in Osaka shown as a white circle. From Google Map

2. Method

PM distribution in East Asia is complex due to both the increasing emissions of anthropogenic particles that are associated with economic growth and the behavior of natural particles. PM has a number of impacts on the social and natural environment. PM affects the Earth's radiation balance due to the scattering and absorbing of solar and thermal radiation as well as by altering the composition of the atmosphere by triggering chemical reactions. Therefore, detailed investigation of atmospheric particles is important. In this study, the characteristics of PM over East Asia were investigated using a combination of ground measurements and model simulations.

2.1 Ground measurements

This study takes advantage of the simultaneous observations made at Osaka's Kinki University campus. In 2002, an AERONET station was set up at the university, which provides measurements of AOT and α. A PM sampler is also installed at the same AERONET site on the roof of a building 50 m above sea level.

The data supplied by the Cimel instrument were analyzed with a standard AERONET processing system to generate values for AOT and α. The AOT resolution was better than 0.01 for all observation wavelengths, and cloud screening was performed on the data before aerosol retrieval [7]. AOT, the basic parameter for describing atmospheric aerosols, indicates the degree of opacity; hence, the atmospheric concentration of aerosol particles [8].

The SPM-613D sampler collects suspended PM on a teflon filter and measures the weight of the particles by the absorbance of a beta ray. The PM sampler provides information separately on the concentrations of $PM_{2.5}$, PM_{10}, and optical black carbon particles because it can separately determine the contributions of fine particles ($PM_{2.5}$) and coarse particles (PM_C) to yield the difference between PM_{10} and $PM_{2.5}$ concentration levels. PM_C is generally a better indicator of dust events than $PM_{2.5}$ because soil dust particles are typically large. A field emission scanning electron microscope (SEM) equipped with an energy-dispersive X-ray analyzer (EDX) is an effective instrument for observing surface microstructures and analyzing the chemical composition of materials such as metals, powders, and biological specimens. An SEM/EDX was used to analyze the PM from the PM sampler. The SEM/EDX can detect elements from a sample, using the X-rays emanating from the surface of the sample to provide the mass concentration of each component.

2.2 Model simulations

The three-dimensional aerosol-transport-radiation model SPRINTARS [9] was driven by the general circulation model of the atmosphere ocean research institute (AORI)/ NIES/ frontier research center for global change (FRCGC) in Japan. The horizontal and vertical resolutions of the triangular truncation were set at T42 (approximately 2.8 by 2.8 degrees in latitude and longitude) and 20 layers, respectively. A simplified mixed-layer ocean was used to simulate sea surface temperature changes driven by aerosols using the prescribed surface heat flux. The model considers carbonaceous, sulfate, dust, and sea salt aerosols, and aerosol transport processes, including emission, advection, diffusion, wet deposition, dry deposition, and gravitational settling. Emission inventory data on fossil fuel consumption, fuel wood consumption, and forest fires were used as inputs for the carbonaceous and sulfate aerosols.

3. Characteristics of particulate matters

Japan's environmental quality standards for $PM_{2.5}$ are a daily air average of 35 $\mu g/m^3$ and an annual air average of 15 $\mu g/m^3$. The annual $PM_{2.5}$ air average at our site was about 20 $\mu g/m^3$, which exceeds Japan's quality standard. This suggests that clear atmospheric conditions are rare in the area and that suspended particles can usually be found in the atmosphere.

3.1 Monthly mean

The SPM sampler measures PM concentrations every hour. Data with missing values and negative values are eliminated. The data is eliminated if the value of PM_{10} concentration is smaller than that of $PM_{2.5}$. After data screening, the daily and monthly PM concentrations were calculated. The monthly mean $PM_{2.5}$ and PM_C concentrations at the Osaka site are shown in Fig. 2. The black and gray lines indicate $PM_{2.5}$ and PM_C concentrations, respectively. The vertical lines show the maximum and minimum values for these measurements. From this data, it is evident that $PM_{2.5}$ concentrations were higher during spring and summer. The concentrations decreased somewhat during the monsoon in June. Although relatively high coarse particle concentrations were measured during spring, overall, fine particle concentrations predominated at the Osaka site.

The AERONET-generated monthly mean AOT and α values at the same site as shown in Fig. 3. AOT is the basic parameter for describing atmospheric aerosols. α is derived from the spectral AOT, as in Eq. (1), where α represents the wavelength.

$$\alpha = -\frac{\ln(AOT(\lambda_2)/AOT(\lambda_1))}{\ln(\lambda_2/\lambda_1)}. \tag{1}$$

The α values are closely related to the aerosol size distribution. Small α values indicate the presence of large particles, and large values indicate small particles. In general, α values from ~0 to 1.0 indicate large particles, such as sea salt aerosols and soil dusts, whereas values of $1.0 < \alpha < \sim 2.5$ indicate sulfate particles and those associated with biomass burning [10]. PM characterized by high AOT and low α values is typical at the Osaka site during the period from March to May, as shown in Fig. 3.

These ground measurements indicate that PM concentrations increase from spring to summer over Osaka and are characterized by a high concentration of coarse particles in spring and a high concentration of fine particles in summer.

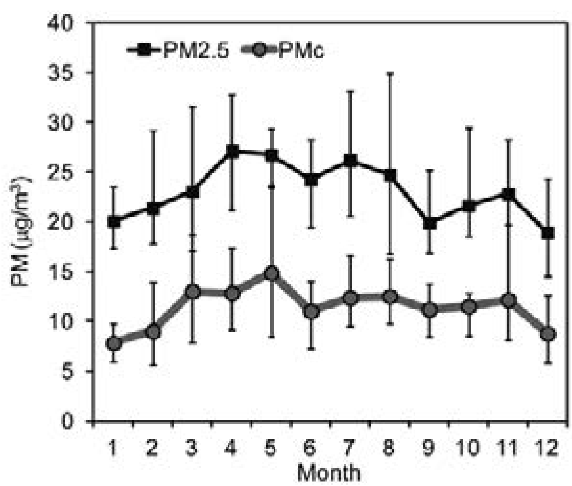

Fig. 2. Monthly mean $PM_{2.5}$ and PM_C concentrations [$\mu g/m^3$] averaged from 2008 to 2013 at the Osaka site (34.65° N, 135.59° E). The vertical lines show the maximum and minimum values for these measurements.

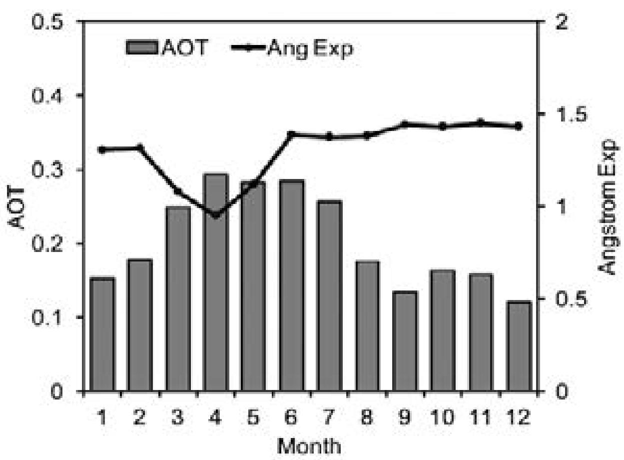

Fig. 3. Monthly mean AERONET AOT and α values averaged from 2008 to 2013 at the Osaka site (34.65° N, 135.59° E).

3.2 Seasonal change factors

Automobiles and factories use fossil fuels, which are important sources of $PM_{2.5}$, during summer and other times of the year. During winter, coal-burning power plants and household heat appliances use increased amounts of fuel. China's Ministry of Environment Protection has reported that up to 25% of the country was covered with a thick fog during the winter of 2012/2013. Since seasonal winds can carry pollution from China to Japan, during winter and spring the northwest winds that dominate in Japan bring increased levels of pollution into the country. In winter, high $PM_{2.5}$ concentrations were observed occasionally, but the monthly mean $PM_{2.5}$ concentrations in Japan were not very high. In addition, the atmosphere was relatively clear in autumn around the site.

Fig. 4 (a) shows the frequency of the daily average $PM_{2.5}$ concentration being higher than 50 $\mu g/m^3$. This frequency was highest in August, followed by May and July. The frequencies of photochemical smog and dust events in the Osaka area are shown in Figs. 4 (b) and 4 (c), respectively. Photochemical smog forecasts and advisories are issued when oxidant concentrations exceed 0.08 ppm and 0.12 ppm, respectively, and suitable weather conditions exist for photochemical reactions. In summer, more sulfate aerosols are produced by active photochemical reactions [11]. Hence, the frequent occurrence of high concentrations of aerosols from July to August is likely caused by photochemical reactions. High $PM_{2.5}$ concentrations were observed at our site when photochemical smog was forecast or when smog advisories were issued for the Osaka prefecture.

The observed dust events likely contributed to the seasonal variations in coarse particle concentrations. The air and ground conditions are suitable for dust events in spring, due to the strong surface winds and dry land conditions. On the other hand, in summer, winds weaken and the lands moisten. Dust events can also occur during autumn in Asia, and dust has occasionally been observed during this season in Japan. Particle properties, such as amount, size, shape, and composition, change in the Osaka area during dust events. The elemental compositions were determined by SEM/EDX analysis on a day with a dust event. On the day without a dust event, the PM_{10} ratio of silicon was approximately 30%. It is clear that silicon, which is possibly from soil particles, was the dominant PM_{10} constituent on the day with a dust event [12]. Since the size of dust particles decreases during long-range transport, the $PM_{2.5}$ concentrations during dust event were high. Furthermore, fine anthropogenic particles can be transported to Japan along with dust particles [12]. Consequently, $PM_{2.5}$

concentrations often increase during dust events.

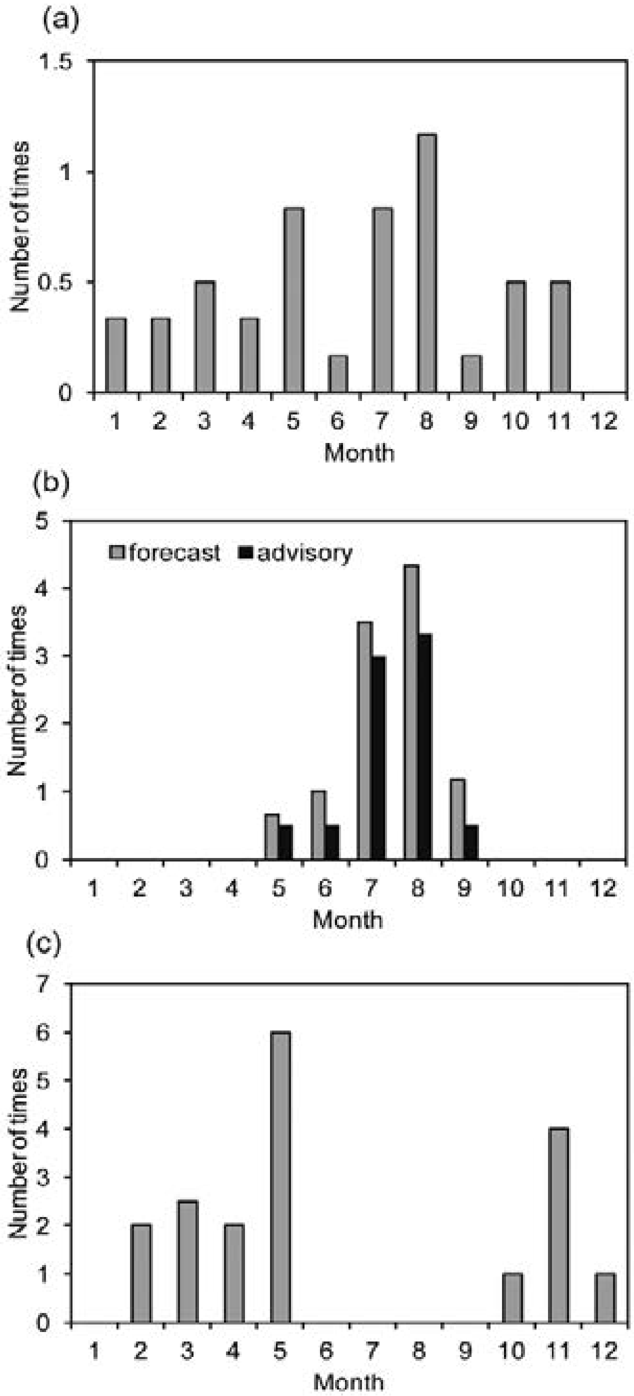

Fig. 4. (a) Number of times daily average $PM_{2.5}$ concentrations at the Osaka site were higher than 50 $\mu g/m^3$ during each month of the year. (b) Number of times that photochemical smog was forecast and advisories were issued in Osaka prefecture. (c) Number of times that a dust event was observed in Osaka prefecture. All data were averaged from 2008 to 2013.

4. PM Influence on radiation budget

In addition to causing air pollution, PM may also affect the radiation budget. Therefore, we utilized model simulations to investigate the influence of these effects.

4.1 Seasonal mean vertical and horizontal distribution of PM

Fig. 5 shows the two-month averaged sulfate aerosol mass concentration and winds at 850 hPa derived from the model simulation. Sulfate aerosol is the major anthropogenic PM emitted from the burning of fossil fuels. In winter, sulfate aerosol is transported from China to western Japan by northwest winds. Therefore, a high concentration of $PM_{2.5}$ is often observed in western Japanese cities when air pollution occurs in eastern Chinese cities. However, the concentration of sulfate aerosol transported to eastern Japan is low in winter. The region of large aerosol concentration extends from western to northern Japan in summer. The vertical distribution of sulfate aerosol concentration from 110° E to 160°E at 35°N is shown in Fig. 6. The sulfate aerosol elevation is low in winter and increases from spring to summer with the presence of warmer surfaces. In summer, weather conditions are also suitable for photochemical reactions. The high concentration of $PM_{2.5}$ in summer at Osaka was caused by these factors.

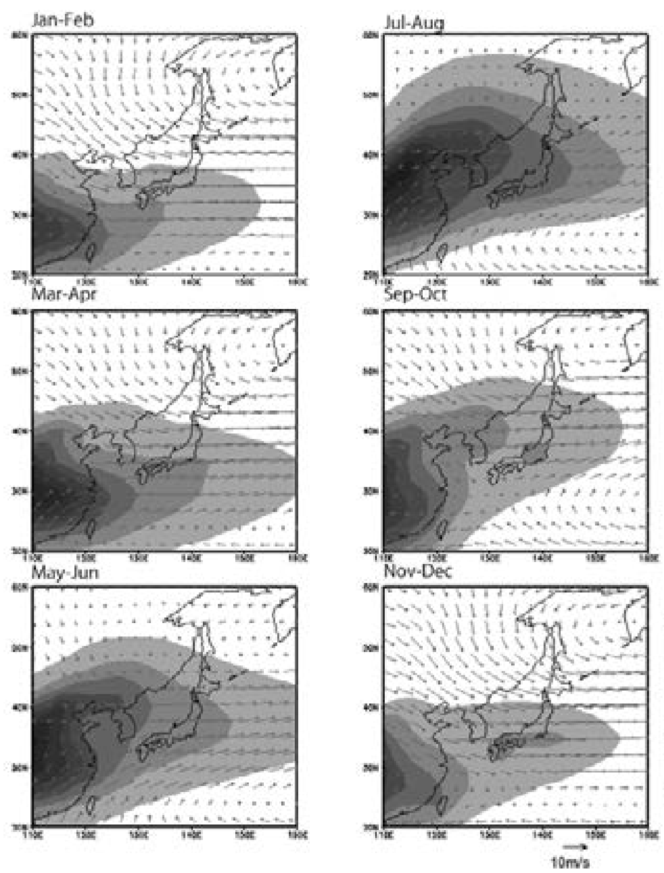

Fig. 5. Simulated two-month averaged sulfate aerosol mass concentration ($\mu g/m^3$) and wind speed at 850 hPa.

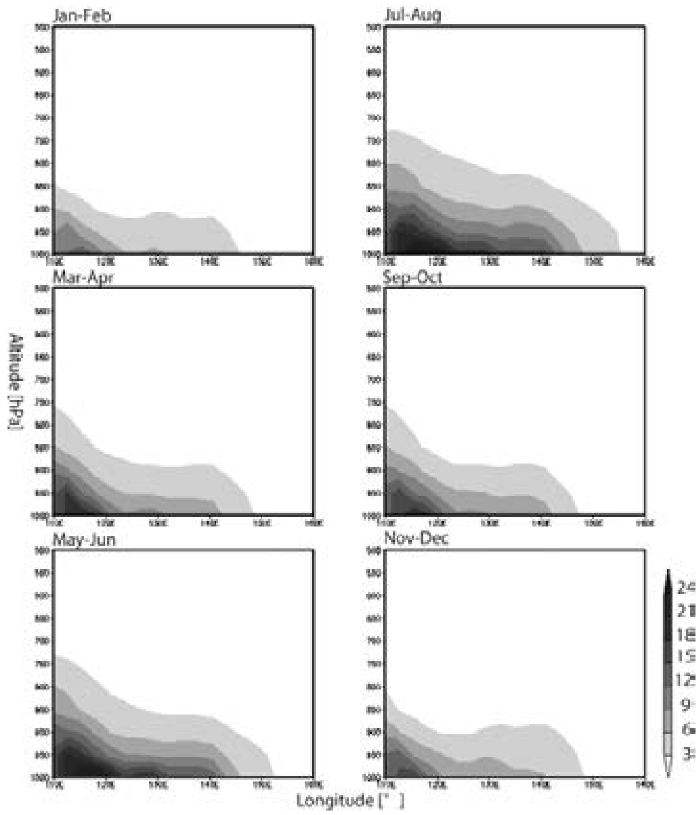

Fig. 6. Simulated two-month averaged vertical distribution of sulfate aerosol mass concentration ($\mu g/m^3$) at 35° N.

4.2 Influence of PM on climate

To investigate the impact of anthropogenic aerosols, two sets of contrasting atmospheric conditions were modeled. The first experiment used present-day (2000) emission data for anthropogenic aerosols (i.e., sulfate and carbonaceous aerosols), and the second experiment used preindustrial (1850) emission data. The inputs of sulfate and carbonaceous aerosols from the burning of fossil fuels were neglected for the preindustrial-era model, and the emission of carbonaceous aerosols from biofuels and agricultural activities were set to one-tenth of present-day values. Both experiments were conducted using present-day greenhouse gas conditions. The differences between the two-modeled experiments were considered to reflect the impact of anthropogenic aerosols on climate.

The influence of anthropogenic aerosol, as estimated from the difference between the two experiments, is shown in Fig. 7. The increase in anthropogenic aerosols causes an increase in the extinction coefficient near the surface and a decrease in solar radiation at Osaka. These changes are particularly large in summer. The active photochemical reactions and the high aerosol values account for the remarkable AOT increase in summer. Therefore, an increase in anthropogenic aerosol concentration leads to a large decrease in solar radiation in summer at Osaka.

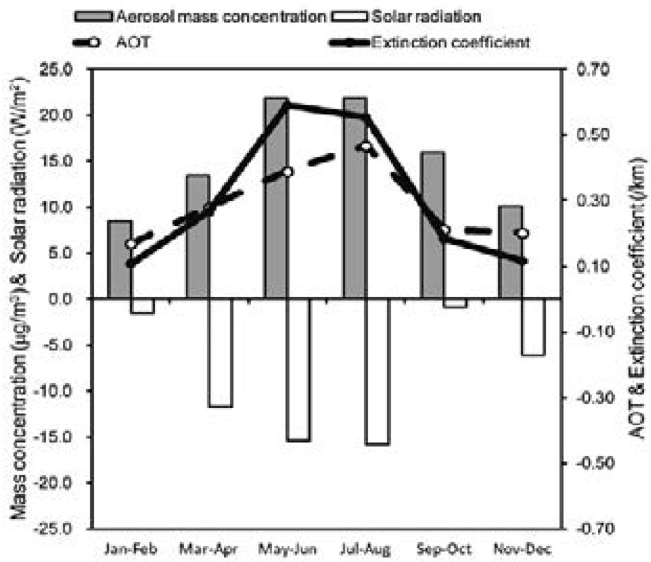

Fig. 7. Differences between the two experiments with respect to AOT, solar radiation, and aerosol mass concentration, and the extinction coefficient near the surface.

5. Summary

Seasonal PM variations around Osaka, which is the second largest metropolitan area in Japan, were investigated. $PM_{2.5}$ concentrations were highest during spring and summer. The spring dust event increased levels of pollution into the region with high concentrations of both coarse and fine particles. Increase of sulfate aerosol concentrations produced by photochemical reactions likely caused the high concentrations of $PM_{2.5}$ during summer. Model simulation results showed that the impact of anthropogenic PM at the observation site is significant in summer.

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