EFFECT OF SAHARA DUST EVENTS ON THE DEPOSITED FRACTION OF ATMOSPHERIC AEROSOL IN THE RESPIRATORY TRACT

M.I. GINI1,2, A. KOTZAMANOGLOU3, C. HELMIS2, M. PILOU3, C. HOUSIADAS3 and K. ELEFTHERIADIS1

1 E.R.L., Institute of Nuclear & Radiological Sciences & Technology, Energy & Safety, NCSR “Demokritos”, Athens, Greece
2 National and Kapodistrian University of Athens, Faculty of Physics, Department of Environmental Physics and Meteorology, University Campus, Athens, Greece
3 THEMLAB, Institute of Nuclear & Radiological Sciences & Technology, Energy & Safety, NCSR “Demokritos”, Athens, Greece

gini@ipta.demokritos.gr

ABSTRACT

Deposition of inhaled atmospheric aerosol particles in the respiratory tract is related to both the physical properties of the particles and the anatomical and physiological characteristics of respiration. Mass size distribution of aerosol particles is an important factor in predicting the deposition fraction of the inhaled particles in various regions of the respiratory tract. Aerodynamic particle size correlates directly with regional deposition in the lungs and the upper respiratory tract. Sahara dust transport is a major source of airborne particulate matter (APM) in the greater Athens metropolitan area. Exceedances of the limit of the PM10 mass concentration due to Sahara dust transport events are often reported. The presence of such high concentrations of mineral dust raises concerns about the impact on human health. In this study the deposited fraction of APM in the human respiratory tract was examined in the case of Sahara and Non-Sahara dust transport events. Mass size distributions of atmospheric aerosol were obtained by means of a low pressure Berner cascade impactor. The measurement campaign took place at the GAW-DEM suburban background monitoring station (Spring 2010), located at the grounds of NCSR “Demokritos”. The Berner impactor consists of 11 stages onto which the particles are deposited according to their aerodynamic diameter and its cut-off diameters ranged between 26 nm and 13 μm. In order to calculate exposure to APM and deposition in the respiratory tract, the Multiple Path Particle Dosimetry model (ARA.inc, CIIT, RIVM) was applied. The MPPD model allows PM deposition fractions of the inhaled aerosol mass to be calculated for given human respiratory tract regions, under different exposure conditions and airway morphometry. For the studied moderate Sahara dust events an average increase of the order of 10 μg/m3 was observed in the PM10 mass concentration. According to the mass size distribution a significant increase was observed for coarse particles (7 μg/m3) and fine particles (3 μg/m3), as well. The results obtained from the dosimetry model showed that the contribution of Saharan dust to the deposited mass of coarse particles in the upper respiratory tract concentration was 63%, compared to the received amounts at background conditions. However, coarse particles can be normally cleared from the upper part of the respiratory system. On the other hand, the contribution of Saharan dust to the deposited mass of coarse particles in tracheobronchial and pulmonary region was 32%. The results obtained from MPPD model were also compared to the results obtained by means of a 1D, mechanistic, respiratory deposition model, based on the Eulerian approach (1D-Eul).

KEYWORDS: health effects, dosimetry model, airborne particulate matter, deposition fraction, Sahara dust
1. INTRODUCTION

During the last decades there is an increasing interest in the physical and chemical characterization of atmospheric aerosol particles. The size distribution of airborne particulate matter (APM) can be used as an indicator for the possible emission sources. Coarse particles originate from many natural (windblown dust, sea sprays, volcanoes) and anthropogenic processes (agriculture, industrial and construction activities), whereas fine aerosol particles originate from primary emissions (fuel combustion) and secondary formation from condensation of precursor gases. Mineral dust is one of the most abundant aerosol types in the natural environment, while Saharan desert is the one of the largest source of mineral dust in the world. The dust particles play an important role in Earth's climate system since mineral particles can act both as ice nuclei to produce ice crystals and as cloud condensation nuclei to produce cloud droplets, modifying the microphysical, optical and radiative properties of clouds. The quantity of the dust-induced radiative forcing depends on the composition, mass and number size distribution of suspended dust, the vertical distribution and the albedo of the underlying surface, resulting to either cooling or warming of the Earth's atmosphere (Levin et al., 1996, Tegen et al., 1997, IPCC, 2007).

Several epidemiological studies indicated a strong correlation between exposure to increased aerosol concentrations and adverse health effects. European Union set the first limit values for PM$_{10}$ at 1999 and has revised them, setting more restrictive limits. According to the Directive 2008/50/EC it is required for annual mean PM$_{10}$ mass concentration to be lower than 40μg/m$^3$, whereas the 24 hour limit value of 50μg/m$^3$ must not be exceeded more than 35 times in a calendar year. However, natural mechanisms can significantly increase the levels of PM$_{10}$ mass concentration. Exceedances of the limit of the PM$_{10}$ mass concentration can be observed due to naturally produced aerosol (dust outbreaks from Saharan desert) in all Southern European countries, since mineral dust can travel thousands of kilometres, affecting many other regions of the world (Engelstaedter et al., 2006, Querol et al., 2009). Therefore, many studies have focused on the estimation of the influence of Saharan dust transport on air quality and health effects (Karanasiou et al., 2012 and references therein).

The objective of this work was to investigate the effect of Sahara dust transport to the aerosol mass size distributions patterns. Moreover, the inhaled lung dose of APM in the case of Saharan and Non-Saharan dust events was examined. The aerosol size distribution is an important factor in predicting the deposited fraction of the inhaled particles in the different regions of the respiratory tract, while aerodynamic particle size governs directly the regional deposition in the lungs and the upper respiratory tract.

2. MATERIALS AND METHODS

2.1 Sampling site

The measurement campaign was carried out from 29 March to 29 May 2010 at the GAW-DEM atmospheric aerosol monitoring station (http://gaw.empa.ch/gawsis/reports.asp?StationID=2076202728), which is located in a suburban area of Athens (Greece). The coordinates of the sampling station are: 37°59′43.21″ N, 23°48′57.16″ E. The sampling site is located on the western hillside of Hymettus mountain, in a vegetated area, away from direct emission sources. It is partly influenced by the urban area and partly by incoming air from the North East, representative of regional atmospheric aerosol conditions.

2.2 Instrumentation

The mass size distributions of atmospheric particulate matter were obtained by means of a low-pressure cascade Berner impactor. Berner impactor consists of 11 stages, yielding aerosol fractionation in 11 size intervals in the size range 0.03-13.35μm at a 26 L min$^{-1}$ flow rate. During the measurement campaign the 24hr samples were collected on Tedlar
foils, greased with apiezon-L dissolved in toluene, in order to eliminate particle bounce-off. In order to determine the aerosol mass concentration, the foil substrates were weighted before and after each aerosol collection, under controlled conditions of humidity and temperature. Prior to weighing, all substrates were placed for at least 48hr in the conditioned weighing room, where the temperature and relative humidity were maintained at 20 ± 1 °C and 50 ± 5%, respectively.

3. DOSIMETRY ANALYSIS

In this study the MPPD dosimetry model (ARA.inc, CIIT, RIVM) and the mechanistic inhalation dosimetry model developed by Mitsakou et al., (2005) were used to perform the dosimetric calculations. A comparison of the derived results from these models was performed. The MPPD model allows PM deposition fractions of the inhaled aerosol mass to be calculated for given human respiratory tract regions, under different exposure conditions and airway morphometry. The model is based on the morphometric data compiled by Yeh and Schum (1980). The Yeh-Schum Single Path symmetric lung model was used for the MPPD, whereas the exposure to the inhaled aerosol was considered at a fixed tidal volume and breathing frequency. Although both deposition and clearance calculations are enabled for constant exposure, only deposition calculations were performed in this study. The input parameters used in our calculation were: upright body orientation, functional reserve capacity (FRC) of 3300 ml, upper respiratory tract volume of 50 ml, tidal volume of 1250ml and breathing frequency 20 breaths/min, under light exercise conditions (ICRP, 1994).

The model (1D-Eul) developed by Mitsakou et al., (2005), solves the aerosol general dynamic equation (GDE) along the flow direction (in one dimension). The particle deposition was assumed to be the result of the mechanisms of gravitational settling, Brownian diffusion and inertial impaction, acting simultaneously. The description of the respiratory tract is based on Weibel’s morphometric model “A” (Weibel, 1963). For the dosimetric calculations the number size distribution was calculated from the mass size distributions, assuming an appropriate particle density for the characteristic size intervals. The input parameters used for the calculations were the same as in the MPPD model.

4. RESULTS

4.1. Mass size distributions

Four mass size distributions during Saharan dust episodes over 24h sampling periods and six mass size distributions under different conditions over the same period of the year were collected. We refer to the results for Saharan dust episodes as “Sahara” and all other results obtained during the non-Saharan regional transport as “background”. The size-fractionated mass distributions derived from the cascade impactor were inverted into smooth mass size distributions by the MICRON inversion code (Wolfenbarger and Seinfeld, 1990). The inverted distributions were integrated to obtain the PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ mass concentrations. During the Saharan dust episodes an average increase in the total PM$_{10}$ mass concentration of around 57% compared to the average mass concentration at background conditions was observed. The contribution of Saharan dust to the PM$_{10}$ mass concentration was 26%. This is in agreement with previous conducted studies in the region of Athens. Mitsakou et al. (2008) reported that the contribution of Saharan dust to the PM$_{10}$ mass concentration in a suburban area of Athens was 25%, which is close to the 21% found by Athanasopoulou et al (2010). Moreover, an increase of 3 μg/m$^3$ was also observed in the PM$_{1}$ mass concentration.

The average aerosol mass size distributions in the “background”cases along with the average mass size distribution during the Saharan dust episodes are presented in Figure 1. As can be seen in this figure, both size distributions show a multi-modal structure. The enhanced particle formation and the coexistence of dust particles, sea-salt and
anthropogenic pollution are the possible reasons of the multiple modes. Modal analysis of the size distributions was performed and their characteristic parameters MMAD (Mass Median Aerodynamic Diameter) and GSD (Geometric Standard Deviation) are listed in table 1.

At “background” conditions, the fine fraction of the size distribution consists of one pronounced mode at 0.4 μm and one more at 0.08 um. In the case of Saharan dust episodes, the fine fraction consisted of the same modes but enhanced mass concentration was found at the 0.4 μm mode. Saharan dust episodes appeared to significantly affect the size distribution of coarse particles, while an increase (9 μg/m³) in the PM_{coarse} mass concentration was observed. During the non-Saharan dust days, the coarse fraction appeared to have a pronounced mode at 2.9 μm. In the Saharan dust episodes case, a distinct mode appeared at 4.1 μm, but an even coarser particles appeared (≈15um) attributed to Saharan dust transport. The mass size distribution of APM in the Saharan dust case had a similar structure to the one presented by Gerasopoulos et al. (2007) in the spring case, but the extra coarse mode appeared to lower MMAD. For the spring period, enhanced concentration of particles with aerodynamic diameters greater than 3μm was also observed.

![Average mass size distributions in the case of Saharan and Non-Saharan dust episodes.](image)

The origin of the air masses ended at DEM station during the sampling period was identified with the 5-day HYSPLIT 4.0 model back-trajectories. Back-trajectories were calculated for the arrival levels of 500, 1000 and 3000 m.a.s.l over the monitoring site, by modeling the vertical velocity. The meteorological input for the trajectory model was the NCEP/NCAR (National Centers for Environmental Protection/National Center for Atmospheric Research) Reanalysis Project database. In Figure 2 the calculated back-trajectories for the air masses ending over Athens during the sampling period at 1.0 km a.s.l. are presented. This figure shows that during the sampling period, four cases (red lines) could be considered representative of Saharan dust episodes. In this figure, the back-trajectories of the air masses for the rest sampling period are also presented.

In order to identify the possible reasons for the increased concentrations of fine particles, the daily mixed layer depth (MLD) was also calculated by means of the HYSPLIT model. It was observed that three of the four Saharan dust events were characterized by an apparent decrease of the MLD over the sampling site, resulting in poor dispersion conditions and high PM concentrations. Under background conditions, the daily average MLD was found equal to 580m, whereas in the case of Saharan dust days it was calculated equal to 320m. The lowest daily PM_{1} mass concentration (6.5 μg/m³) was
observed when the daily MLD was 900 m (non-Saharan dust day). It is worth to mention that the highest average PM$_1$ mass concentration (16.9 µg/m$^3$) was observed when the daily MLD depth was 190 m (Saharan dust day). This result is in agreement with a previous study (Kallos et al., 2007), according to which the coexistence of PM from both anthropogenic and natural origin is favored by the same type of synoptic weather: the formation of a southerly or southwesterly flow in the lower troposphere. This kind of synoptic flow associated with certain large scale surface pressure gradient and vertical thermal structure (affected by thermal advection) of the lowest 3 km, which are related with the efficiency of horizontal (mechanical) and vertical (thermal-convective) mixing (Helmis et al, 1997), are responsible for stabilizing the lower troposphere by transferring warm, dry air masses and creating poor dispersion conditions over the Athens Metropolitan Urban Area, resulting in increased PM levels.

**Fig. 2:** 5-days air mass back trajectories analysis at 1000km a.s.l. (HYSPLIT model, NOAA)

4.2. Inhalation dose
The deposited fraction of particulate matter in various regions of human respiratory tract was calculated by means of the MPPD model and the 1D-Eul, as well. The aerosol mass size distributions of measured by means of the cascade epiphanimeter were fitted by a sum of log-normal distributions. Each one of these distributions had a characteristic MMAD (mass median aerodynamic diameter) and a GSD (geometric standard deviation). For the MPPD model, the contribution of each one of the observed modes to the mass of inhaled particle deposited in different regions of the human respiratory tract was calculated (Table 1). Moreover, the mass size distributions were transformed to number size distributions in order to perform the dosimetric calculations by means of the 1D-Eul model.

In order to perform these calculations the density of aerosol particles have to be known. In this work, considering the fine fraction as a mixture of organics and sulfates, we had applied a mean density equal to 1.5 g cm$^{-3}$ (Pitz et al., 2003). This fraction is not affected by Saharan dust transport but it is related to local anthropogenic emission sources or regional aerosol particles of similar nature. Therefore, the same value was used for both cases, Saharan and Non-Saharan dust days. For the coarse fraction density was assumed to be equal to 2.0 g cm$^{-3}$ (Tegen et al., 2006, Ott et al., 2008), as representative of dust particles (resuspended road dust particles and other fugitive dust for the background conditions). However, in the case of Saharan dust events the “dust” density was set equal to 2.5 g cm$^{-3}$ taking into consideration the contribution of Saharan mineral dust ($\rho=2.65$ g cm$^{-3}$) to the coarse fraction (Pitz et al., 2003).
In Table 1 the fraction of the inhaled particle mass (MPPD) and number (1D-Eul) deposited in different respiratory regions (H-Head, TB-tracheobronchial, P-Pulmonary) is presented for both cases, Saharan and non-Saharan dust days. It was observed that more than 80% of the inhaled PM mass was deposited in the upper region of the respiratory tract. The increase in average mass concentration in the coarse mode (15 μg/m³) corresponds to an increase in the deposited mass concentration more than 160.0 μg/day (16h exposure, light exercise) in the upper respiratory track. The increase in the dust (coarse particles) mass deposited in the trachea-bronchia and pulmonary regions was about 10 μg/day. However, Mitsakou et al. (2008) reported extremely high mass deposited values for the days of severe dust episodes, reaching up to 600 μg/day (6h exposure). In that study the Saharan dust levels in Greece and the received inhalation doses were also examined but only the PM₁₀ mass concentration were available. The size distributions for the calculation of the inhaled doses were obtained, employing a long-range transport mode with MMD equal to 2.524 μm and GSD equal to 2.

The increase in the mass concentration of the fine fraction which was observed when Saharan dust events occurred, leads to an increase in the deposited mass in the trachea-bronchia and pulmonary regions of ~25% (according to both models), compared to the average mass concentration at background conditions.

**5. CONCLUSIONS**

The results of this study confirm that Saharan dust transport significantly increase the PM₁₀ mass concentrations. For the studied Sahara dust events an increase of the order of 10 μg/m³ (57%) was observed in the average PM₁₀ mass concentration compared to the average mass concentration at background conditions. PM₁₀ originated mainly from anthropogenic sources. However, an increase in the mass concentration of fine particles was also observed. The lower mixed layer depth over urban environment during the Saharan dust episodes could be the main reason for the enhanced PM₁₀ mass concentrations. The mass size distributions had a multi-modal structure indicating the different emission sources of APM, in both cases. Under background conditions, the average mass size distribution had two distinct modes at 0.4 μm and 2.8μm. In the Saharan dust case, the mass size distribution appeared to have one more pronounced mode at ~15μm. The contribution of each one of the observed modes to the mass of inhaled particle deposited in different regions of the human respiratory tract was calculated by means of the MPPD model and the 1D-Eul model, as well. The results of
both deposition models were in good agreement. In particular, the contribution of Saharan dust events to the deposited mass of coarse particles in the upper respiratory tract concentration was 63% and 66% for the MPPD and the 1D-Eul, respectively. Less than 10% of the inhaled mass of coarse particles was deposited in the pulmonary region of the lung. However, when severe dust transport events occur extremely high mass deposited values in the respiratory tract can be obtained. According to the MPPD model, the contribution of Saharan dust events to the deposited mass of coarse particles in the TB and P region was 30% and 32%, respectively. The corresponding values according to the 1D-Eul model were 32% and 44%, respectively. The deviation between the two models is attributed to the different lung morphometric models they employ.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (http://www.arl.noaa.gov/ready.html) used in this publication. We also acknowledge ARA (About Applied Research Associates, Inc) for allowing us to use the MPPD program.

REFERENCES


