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PM₁₀ Concentration levels at an urban and background site in Cyprus: The impact of urban sources and dust storms

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Abstract

Air quality in Cyprus is influenced by both local and transported pollution including desert dust storms. We examined PM₁₀ concentration data collected in Nicosia (urban representative) from April 1, 1993 through December 11, 2008, and Ayia Marina (rural background representative) from January 1, 1999 through December 31, 2008. Measurements were conducted using a Tapered Element Oscillating Micro-balance (TEOM). PM₁₀ concentrations, meteorological records and satellite data were used to identify dust storm days. We investigated long term trends using a Generalized Additive Model (GAM) after controlling for day of week, month, temperature, wind speed, and relative humidity. In Nicosia, annual PM₁₀ concentrations ranged from 50.4 to 63.8 µg/m³ and exceeded the EU annual standard limit enacted in 2005 of 40 µg/m³ every year. A large, statistically significant impact of urban sources (defined as the difference between urban and background levels) was seen in Nicosia over the period 2000–2008, and was highest during traffic hours, weekdays, cold months, and low wind conditions. Our estimate of the mean (standard error) contribution of urban sources to the daily ambient PM₁₀ was 24.0 (0.4) µg/m³. The study of yearly trends showed that PM₁₀ levels in Nicosia decreased from 59.4 µg/m³ in 1993 to 49.0 µg/m³ in 2008, probably in part as a result of traffic emission control policies in Cyprus. In Ayia Marina, annual concentrations ranged from 27.3 to 35.6 µg/m³, and no obvious time trends were observed. The levels measured at the Cyprus background site are comparable to background concentrations reported in other Eastern Mediterranean countries. Average daily PM₁₀ concentrations during desert dust storms were around 100 µg/m³ since 2000 and much higher in earlier years. Despite the large impact of dust storms and their increasing frequency over time, dust storms were responsible for a small fraction of the exceedances of the daily PM₁₀ limit.

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Introduction

The Eastern Mediterranean basin experiences high particulate matter (PM) levels from sources such as traffic, sea salt, dust resuspension, and emissions from industrialized European countries (Dayan et al., 1991; Kubilay and Saydam, 1995; Güllü et al., 2000; Kubilay et al., 2000; Querol et al., 2009). The area is also impacted hugely by desert dust storms originating mostly from North Africa and to a lesser extent from the Arabian Peninsula (Ganor et al., 1991; Kleanthous et al., 2009; Bari et al., 2009; Querol et al., 2009). During these events, which can last for several days, PM₁₀ (particulate matter with aerodynamic diameter less than 10 µm) concentrations are considerably higher than the 2005 European Union (EU) daily limit value of 50 µg/m³ (Rodríguez et al., 2001; Koçak et al., 2007; Mitsakou et al., 2008; Querol et al., 2009). A number of epidemiological studies have associated exposure to ambient PM₁₀ during desert dust outbreaks with increased cardiovascular and respiratory hospital admissions or even mortality (Bell et al., 2008; Middleton et al., 2008; Grineski et al., 2011; Mallone et al., 2011; Barnett et al., 2012; Kashima et al., 2012; Neophytou et al., 2013).

In Cyprus, an island sited in the eastern Mediterranean, a prior study reported relatively high concentrations for nitrogen dioxide (NO₂), benzene, and PM in urban areas, and ozone (O₃) in the mountainous areas (Baumbach and Pfeiffer, 2004). PM₁₀ levels were previously reported to be much higher in Cyprus compared to other European countries and they exceeded the EU air quality standards (Baumbach and Pfeiffer, 2004; Kleanthous et al., 2009). The national action plan for the improvement of ambient air quality in Cyprus considers pollution derived from industrial sites, cars, central heating, airplanes, ships, and even natural sources. For this purpose, the Cypriot Ministry of Labour and Social Insurance is monitoring the air quality continuously at different sites across the island. While monitoring of PM pollution begun about two decades ago, there has been no assessment to evaluate long-term trends in Cyprus air quality until now.

This study describes the PM₁₀ concentrations in an urban (Nicosia—capital city) and a background (Ayia Marina) monitoring sites in Cyprus and evaluates the pollution trends, impact of changes in fuel use, and frequency of desert dust storm events over a 16-year study period (1993–2008). In addition, it examines the diurnal, weekday, and seasonal variations of urban PM₁₀ concentrations.

Material and Methods

Monitoring sites description

We used PM₁₀ data from an urban representative site at the Old General Hospital in Nicosia (35–10′19.2″ N, 33–21′10.8″ E) and a rural background representative site in Ayia Marina Xyliatou village (35–02′08″ N, 33–03′26″ E). Ayia Marina is located in the Nicosia district, approximately 40 km southwest of the city, and is situated 450 m above sea level (Figure 1). Both sites are located in the inland area and experience hot dry summers and mild winters. Over the eastern Mediterranean, surface winds are mostly westerly or southwesterly in the winter and northwesterly or northerly in the summer. Over Cyprus winds are quite variable in direction and strength, and they are influenced by (a) eastward-moving cyclones crossing

the Mediterranean Sea, the continental anticyclone of Eurasia, the low-pressure belt of North Africa in the winter, and the Indian monsoon low in the summer; (b) orography; and (c) large temperature differences between land and sea (sea and land breezes). The annual mean wind speed in inland locations (3–5 m/s) is lower than those in coastal (2–6 m/s) and mountainous areas (5–7 m/s). The prevailing wind directions are south or southwesterlies during the day and northwesterlies or northeasterlies during the night (Paschardes and Christofides, 1995). On average, Ayia Marina is downwind of Nicosia during the night and the opposite effect occurs during the day.

Nicosia Old General Hospital and Ayia Marina Xyliatou were characterized as “traffic” and “background” representative sites, respectively, by the Department of Labour Inspection (DLI), Ministry of Labour and Social Insurance. This characterization is according to the criteria set by Cyprus and European Union legislation (Ambient Air Quality Law of 2002 (N.188(I)/2002), Ambient Air Quality (96/62/EC)). The Ayia Marina background monitoring station is included in the network of the Co-operative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP). This site is mostly impacted by transported pollution reaching Cyprus and to a lesser extent by sea salt and local soil dust (Kleanthous et al., 2007). The reported lack of morning and evening concentration peaks provided some evidence that this site is not impacted by local traffic.

Data collection

Hourly PM₁₀ concentrations at these two sites were monitored using a Tapered Element Oscillating Micro-balance (TEOM) and were obtained from the DLI. Data from the Nicosia urban site were available from April 1, 1993, through December 11, 2008; however, data from the Ayia Marina back-ground site were only available from January 1, 1999, through December 31, 2008. For both sites, daily PM₁₀ averages were calculated for days with at least 12 hourly measurements. DLI refers to the European, EN 12341, filter-based gravimetric reference method for the calibration of TEOM PM₁₀ measurements. For a more detailed description of the reference method and the sampling equipment, the reader is referred to the Baumbach and Pfeiffer (2004) report.

Assuming that the impact of transported particles and local natural particles, such as soil and sea salt, is the same at the urban and background sites, then concentration differences between these two sites reflect the minimum impact of Nicosia urban sources on PM₁₀ concentration levels in Nicosia. Therefore, we calculated the concentration differences for each hourly data point for which we had measurements from both sites and created a new variable, “PM₁₀ urban source contributions.” Daily PM₁₀ averages for the urban contributions were also calculated. A similar approach was previously used to assess the impact of urban sources in Spain (Moreno et al., 2005).

Meteorological data including temperature, relative humidity, wind speed, precipitation, and dew point were also obtained for the duration of the study from the Nicosia (Athalassa) meteorological station (Cyprus Meteorological Service).

Desert dust storms identification

We referred to procedures described in the 2002 European Commission report, “Guidance to Member States on PM₁₀ Monitoring and Inter-Comparisons With the Reference Method,” to identify high PM₁₀ levels associated with dust storm events. We also used a combination of approaches to identify desert dust storm events as follows:

1. We defined days of ‘high PM₁₀ levels’ as the days with mean daily concentration above the 95th percentile value of 100 and 50 µg/m³ in Nicosia and Ayia Marina, respectively.
2. We used records for days of noted poor visibility due to suspended dust from observations at the Larnaca airport (code 06), provided by Cyprus Meteorological Service.
3. We used daily measurements of SeaWiFS (Sea-viewing Wide Field-of-view Sensor) aerosol optical depth (AOD) and Angstrom exponent values for 1998–2008 from the Giovanni online data system, developed and maintained by the National Aeronautics and Space Administration, Goddard Earth Sciences Data, and Information Services Center. High AOD values indicate high total atmospheric column particle concentrations and low Angstrom exponent reflects coarse particle size. A combination of high AOD (>0.3) values and a low Angstrom exponent (<0.9) was used as an indication of the presence of desert dust particles. A similar AOD cutoff value for dust storms was suggested in the analysis of Saharan dust particles from MODIS data over Mediterranean region from Barnaba and Gobbi (2004).
4. We confirmed dust storm events originating from the Sahara or the Arabian Peninsula by examining the 5-day back-wind trajectories reaching the urban and background sites using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model to track the possible dust source (Draxler and Rolph, 2013). Back-trajectories were calculated for three different altitudes (500, 750, and 1000 m above ground level [A.G.L.]) using isentropic meteorological models. Satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS) Atmosphere were also used as an additional tool to verify dust events.

Other desert dust storm identification approaches reported in the 2002 European Commission report and successfully applied by other investigators, involve the use of PM_{2.5} (particulate matter less than 2.5 µm) and total suspended particles (TSP) or PM₁₀ measurements and elemental speciation analysis data (Querol et al., 1998; Querol et al., 2001; Amodio et al., 2008; Amodio et al., 2011). However, these approaches were not applicable in our investigation, which relied entirely on hourly PM₁₀ measurements (from TEOM). PM₁₀ chemical speciation data and simultaneous PM_{2.5} or TSP measurements were also not available. Finally, neither satellite nor PM₁₀ background concentration data were available for the period 1993–1997, and thus we started using satellite and background data after 1997. We would expect that we missed some dust storm days and therefore our estimates of dust contribution for the earlier years might underestimate the real contribution.

Data analysis

Annual and monthly dust effect—We used linear regression analysis to estimate the yearly (eq 1) and monthly (eq 2) impacts of dust storms on daily PM₁₀ concentrations, separately for Nicosia and Ayia Marina, as follows:

$$\mu_i = \beta_0 + \beta_{1d} \text{dow}_d + \beta_{2j} \text{month}_j + \beta_{3k} \text{year}_k + \beta_{4k} \text{year}_k * \text{dust}_i \quad (1)$$

$$\mu_i = \beta_0 + \beta_{1d} \text{dow}_d + \beta_{2j} \text{month}_j + \beta_{3j} \text{month}_j * \text{dust}_i \quad (2)$$

where μ_i is the PM₁₀ concentration on a day i , β_0 is the regression intercept, and β_{1d} , β_{2j} , β_{3k} , β_{3j} , and β_{4k} are the regression coefficients for the categorical variables: day of the week (dow_d , $d = 1-7$ [Sunday to Saturday]), month of the year (month_j , $j = 1-12$ [January to December]), year (year_k , $k = 1993-2008$ [Nicosia] or $1999-2008$ [Ayia Marina]), and the interaction term of month (or year) and desert dust storm day (dust_i : 1 if day i was a desert dust storm day, 0 otherwise). The reference day, month, and year were set as Saturday, December, and 2008, respectively.

To estimate the contributions of desert dust storm days to the yearly concentrations we used model 1 to predict yearly averages for days with desert dust storms, and subsequently, we multiplied them by the fraction of desert dust storm days for the respective year k , $f_k = (\text{number of desert dust storm days in year } k)/365$. We estimated the contribution of non-dust storm days to the yearly average in the same way. Finally, using the same approach with model 2, we estimated the contribution of desert dust and non-dust storm days to the monthly concentrations.

PM₁₀ trends—We also examined the nonlinear effect of meteorological parameters, weekday, month and year on PM₁₀ concentrations using a Generalized Additive Model (GAM) with penalized splines (Barmpadimos et al., 2011), as shown in eq 3. This same model was used to study the trends of Nicosia and Ayia Marina PM₁₀ concentrations, and urban contributions:

$$\mu_i = \beta_0 + \beta_{1j} \text{month}_j + \beta_{2d} \text{dow}_d + f_1(\text{day}_i) + f_2(\text{temp}_i) + f_3(\text{ws}_i) + f_4(\text{rh}_i) \quad (3)$$

where μ_i is the mean daily PM₁₀ concentration for day i ; β_0 is the regression intercept; β_{1j} and β_{2d} are the regression coefficients of the independent categorical variables: month_j as the month of the year, $j = 1-12$ (January to December) and dow_d as the day of the week, $d = 1-7$ (Sunday to Saturday), with January and Sunday as the reference month and weekday; $f()$ represents a penalized regression spline function where the degrees of freedom were determined by choosing the smoothing parameter with the option *sp* because of overfitting for f_1 or by Generalized Cross Validation criterion (GCV) for f_2 , f_3 , and f_4 , for the continuous variables: day_i , $i = 1$ to 4,999 for Nicosia and $i = 1$ to 3,011 for Ayia Marina; temp_i is the mean temperature (°C) for day i ; ws_i is the mean wind speed (m/sec) for day i ; and rh_i is the mean relative humidity (%) for day i . Dust days were excluded in the trends analyses.

The impact of fuel use on PM₁₀ trends was examined by adjusting eq 3 with leaded and unleaded gasoline and diesel fuel sales (tonnes per month), having each fuel type as a non-linear variable in the model each time, as follows:

$$\mu_i = \beta_0 + \beta_{1j} \text{ month}_j + \beta_{2d} \text{ dow}_d + f_1(\text{day}_i) + f_2(\text{temp}_i) + f_3(\text{ws}_i) + f_4(\text{rh}_i) + f_5(\text{fuel}) \quad (4)$$

Monthly data on fuel use were available only for the period 2003–2008.

Precipitation and dew point were found to be not statistically significant and thus were not included in the final model. Analyses were performed using the SAS 9.2 (SAS Institute Inc., Cary, NC, USA) and R version 2.14.2 (R Development Core Team) statistical packages.

Results and Discussion

PM₁₀ concentrations and seasonal trends

We examined PM₁₀ concentrations and their trends at the Nicosia urban and Ayia Marina background sites during the period 1993–2008. In addition, we identified dust events and examined their frequency, temporal trends, and monthly and yearly contribution to the total PM₁₀ levels. To the best of our knowledge, this is the first time that this type of analysis has been conducted in Cyprus.

The average daily PM₁₀ concentration at the urban site was 56.0 µg/m³ with a standard error of 0.6 µg/m³. The average concentration after excluding desert dust storm days was 52.6 µg/m³. The overall PM₁₀ average at the background site was 31.2 µg/m³ with a standard error of 0.7 µg/m³, and when desert dust storm days were excluded from the analysis, the average value decreased to 26.1 µg/m³.

Figure 2 depicts the annual PM₁₀ concentrations and the respective dust contributions estimated using eq 1. As can be seen, the annual mean levels in Nicosia exceeded the EU annual standard limit enacted in 2005 of 40 µg/m³ every year. PM₁₀ yearly concentrations at this urban site ranged from 50.4 µg/m³ (1995) to 63.8 µg/m³ (1998). After excluding desert dust days, the concentrations ranged from 48.3 µg/m³ (2002) to 59.4 µg/m³ (1993). The yearly levels at the Ayia Marina background site were lower than those at the urban site and did not exceed the annual 2005 EU standard, ranging from 27.3 µg/m³ (2002) to 35.6 µg/m³ (2008). For non-dust storm days, the yearly means varied between 24.7 µg/m³ (2007) and 30.2 µg/m³ (1999). The mean annual desert dust contribution was estimated to be 6.0 µg/m³ (95% CI: 5.3, 6.8) in Nicosia and 6.8 µg/m³ (95% CI: 5.8, 7.8) in Ayia Marina. The impact of desert dust storms on PM₁₀ concentrations at the urban and background sites is similar, as indicated by the reasonable agreement between impact estimates obtained for these two sites.

Querol et al. (2009) estimated the mean annual net dust contribution in Ayia Marina for the period 2003–2006 to be 9.0 µg/m³. Using our statistical approach, our estimate of the dust contribution was about 20% lower during the same years (7.3 µg/m³). Different desert dust storm identification approaches and statistical analysis methods were used in the two studies, and that is why we got a different estimate. In the study mentioned previously, dust

storms were identified based on meteorological and aerosol maps, satellite SeaWiFS imagery, and HYSPLIT back-trajectories. Dust PM_{10} load was quantified based on the application of a monthly moving 30th percentile to PM_{10} data series, after excluding days with African dust influence. For the desert dust days, the net dust load was obtained by subtracting the calculated 30th percentile to the measured PM_{10} concentration. In our study, we identified dust storms based on ground-level PM_{10} concentrations, airport observations, SeaWiFS data (AOD, Angstrom exponent), HYSPLIT back-trajectories, and MODIS images. Dust annual contribution was estimated using a regression model as explained in the Methods section.

Overall, annual average PM_{10} levels in Nicosia were comparable to those observed in other eastern Mediterranean urban sites, such as Heraklion, Greece ($51 \mu\text{g}/\text{m}^3$), Istanbul, Turkey ($47 \mu\text{g}/\text{m}^3$), and Tel Aviv, Israel ($57 \mu\text{g}/\text{m}^3$) (Dayan and Levy, 2005; Karaca et al., 2005; Gerasopoulos et al., 2006). However, PM_{10} annual levels in Nicosia are higher than those observed in other urban areas in Europe ($20\text{--}55 \mu\text{g}/\text{m}^3$), and levels at Ayia Marina are higher than those seen at most rural sites in Europe ($7\text{--}30 \mu\text{g}/\text{m}^3$) (Querol et al., 2001; Viana et al., 2003; Van Dingenen et al., 2004). Eastern Mediterranean urban and rural sites can be impacted by local soil and sea salt particles, which may explain, in part, their higher levels compared to other European sites. PM_{10} speciation analysis conducted by Querol et al. (2009) shows that mineral dust contributions to the mean annual background particle concentrations are 39% and 25% for the cities of Finokalia (northern coast of Crete, Greece) and Erdemli (southern coast of Turkey), respectively. The same analysis reports sea spray to be responsible for 8% of the mean annual background particle concentrations in Finokalia and 24% in Erdemli.

Figure 3 shows the monthly mean PM_{10} concentrations and the respective desert dust storm contributions at the Nicosia and Ayia Marina sites, which were estimated using eq 2. These results suggest that PM_{10} levels in Nicosia exhibit little seasonal variability, with concentrations slightly higher from November through February and slightly lower in June. In contrast, the background site shows a seasonal pattern with higher levels from February to May due to desert dust storms. In addition, levels at Ayia Marina were higher during the summer (from July to August), possibly due to a number of reasons, such as regional transport, enhanced photochemical activity, lower precipitation, and increased soil resuspension. As shown, desert dust events occurred more frequently during late winter and in spring and, as expected, both sites were similarly impacted by them.

Annual PM_{10} trends

Once the impact of days with dust storms has been excluded, it becomes clear that the yearly PM_{10} mean concentrations in Nicosia decreased from $59.4 \mu\text{g}/\text{m}^3$ (95% CI: 57.1, 61.4) in 1993 to $49.0 \mu\text{g}/\text{m}^3$ (95% CI: 47.3, 50.8) in 2008. Figure 4 shows the temporal patterns of PM_{10} values in Nicosia and Ayia Marina, which have been adjusted to remove the effect of dust storms and to account for the influences of month, day of week, and weather (eq 3). The figure also includes a similar plot of an estimate of the urban contribution adjusted in this same way. As can be seen, the downtrend for Nicosia was not monotonic. From 1993 to early 2001 concentrations decreased by 21% ($12.7 \mu\text{g}/\text{m}^3$). After 2001, we observed an

increase of 13.5% ($6.5 \mu\text{g}/\text{m}^3$), which peaked in mid-2005. Subsequently, PM_{10} levels decreased again by 9.4% ($5.2 \mu\text{g}/\text{m}^3$) from mid-2005 until 2008. Because data from the Ayia Marina background site were not available for years before 1999, we could only examine the trends of background levels and urban source contributions from 1999 to 2008. No significant temporal trends in PM_{10} concentrations were observed at the background site. Urban source contributions in Nicosia exhibited a similar temporal trend to those of PM_{10} concentrations at this site. The average urban contributions were $23.3 \mu\text{g}/\text{m}^3$ (95% CI: 20.7, 26.0) in 1999 and $20.0 \mu\text{g}/\text{m}^3$ (95% CI: 18.2, 21.8) in 2008. From 1999 until early 2001, PM_{10} decreased by 5.6% ($1.3 \mu\text{g}/\text{m}^3$), then increased again by 36.4% ($7.7 \mu\text{g}/\text{m}^3$) until mid-2005, when it decreased again by 28.3% ($8.2 \mu\text{g}/\text{m}^3$) until 2008.

Variation in urban source contributions to PM_{10} concentrations in Nicosia could be related to changes in traffic emissions. There are several factors which may support this, such as:

1. During the 1993–2008 period the total number of vehicles in Nicosia increased by 67.6% (Licensed Vehicles by District, 1990–2011, Cyprus Statistical Service).
2. Unleaded gasoline was first introduced in Cyprus in 1992 and was used concurrently with leaded gasoline until 2004. Since 2005 only unleaded motor gasoline has been used (Sales of Petroleum Products by Type, 1966–2011, Cyprus Statistical Service). It is known that vehicles powered by unleaded gasoline emit less particulate matter than those using leaded gasoline (Yuan et al., 2000). Therefore, the phase out of leaded gasoline might be one of the reasons that PM_{10} decreased in Nicosia.
3. In 2002, Cyprus authorities started implementing new regulations regarding emission standards for newly registered vehicles including: periodic inspections of in-use vehicles and fuel quality specifications (Legislation and policy options for reduction of traffic emission in Cyprus, LIFE00 TCY/CY/051, Department of Electrical and Mechanical Services, Ministry of Communications and Works, Republic of Cyprus).

Note however, that we did not observe any significant reduction in the Nicosia concentrations of PM_{10} or in the estimated urban contributions to PM_{10} between 2003 and 2009 once we had adjusted for changes in fuel use (eq 4).

Dust storm impact on daily concentrations

Table 1 summarizes the PM_{10} mean daily concentrations during desert dust storms and the number of days with PM_{10} concentrations exceeding the daily EU limit of $50 \mu\text{g}/\text{m}^3$. At Nicosia, standard violations occurred 39.0% (2002) to 67.8% (1993) of the days, where a very small fraction of them (1% to 9%) were attributed to desert dust events. At Ayia Marina, the percentage of days exceeding the limit varied between 7.2% (2005) and 11.0% (2008). The contribution of desert dust storms to the daily exceedances was similar, ranging from 3% to 9%. The PM_{10} mean daily concentrations during desert dust storms ranged from $55.5 \mu\text{g}/\text{m}^3$ (1995) to $470.1 \mu\text{g}/\text{m}^3$ (1996) in Nicosia and from $68.1 \mu\text{g}/\text{m}^3$ (2002) to $157.9 \mu\text{g}/\text{m}^3$ (2006) in Ayia Marina. These concentrations show that desert dust storm days have

been typically about $100 \mu\text{g}/\text{m}^3$ since 2000, but in earlier years dust storm days were much worse, averaging $470 \mu\text{g}/\text{m}^3$ in 1996.

We examined the annual frequency of desert dust storms only for the period of 1998–2008 because satellite data and background measurements were not available for the previous years (1993–1997). During the period of 1998–2008 the incidence of dust days in Cyprus increased at an average rate of 1.7 days per year from 7 in 1998 to 36 in 2008 (Figure 5). Our findings are consistent with those of other studies in the Mediterranean region that report an increase in the frequency of dust episodes (Goudie and Middleton, 2001; Kashima et al., 2012), possibly due to climatic changes, such as more droughts, and human disturbance of desert surfaces, such as vegetation removal.

Urban source contributions

The mean impact of urban sources to PM_{10} concentrations in Nicosia for the period 1999 to 2008 was $24.0 \mu\text{g}/\text{m}^3$ with a standard error of $0.4 \mu\text{g}/\text{m}^3$. This corresponds to 43% of the total PM_{10} concentrations.

Nicosia urban source contributions exhibited a strong seasonal pattern, with higher levels observed between November and February (Figure 3). During these winter months, average temperature and wind velocity were at their lowest, favoring the accumulation of local emissions due to reduction in both vertical mixing and horizontal movement of air masses.

We investigated the weekday and diurnal patterns of the urban source contributions. Values were consistent with traffic patterns, which are heavier during the week and lighter on weekends (Table 2).

Diurnal variations in urban source contributions are graphically presented in Figures 6a and 6b. During the cold season (November through April), two peaks were observed during 7:00–9:00 h and 18:00–21:00 h, shown in Figure 6a, which are due to the morning and evening traffic, respectively. During the warmer months (May to October), a peak was noticed between 6:00 and 8:00 h due to the morning traffic but the effect of evening traffic was not very noticeable. During winter, the evening peak is more pronounced than that in the warm season possibly due to the higher atmospheric stability of the cold season. The elevated urban source contributions during traffic time periods clearly indicate a high influence of vehicular emissions.

Conclusions

In this study, we examined the yearly trends and intra-annual variability of PM_{10} concentrations at the Nicosia urban and Ayia Marina background representative sites in Cyprus.

Yearly PM_{10} concentration levels in Nicosia ranged between 50.4 and $63.8 \mu\text{g}/\text{m}^3$ and exceeded the European Union annual standard of $40 \mu\text{g}/\text{m}^3$ during every year of the 16-year study. The study of yearly trends showed that PM_{10} levels in Nicosia decreased over the period 1993 to 2008, probably in part as a result of traffic emission control policies in Cyprus.

PM₁₀ mean concentrations during dust storm days are typically about 100 µg/m³ since 2000, but in earlier years levels on dust storm days were much worse, averaging 470 µg/m³ in 1996. Furthermore, from 1998 to 2008 the number of desert dust days increased at an average rate of 1.7 days per year. Despite the large impact of dust storms on annual average PM₁₀ concentrations and the increasing frequency of dust storms over time, dust storms were responsible for a small fraction of the exceedances of the daily PM₁₀ limit.

Urban sources in Nicosia were responsible for 43% of the total PM₁₀ concentrations. The impact of the urban source contributions was higher during traffic hours, weekdays, cold months, and low wind conditions, indicating that these contributions are mostly originating from traffic emissions.

Finally, it must be noted that in this paper we assess and discuss the impacts of dust storms, which should not be confused with the contributions of other natural particles such as local resuspended soil and sea salt. It is conceivable that the Earth crust and the sea are major sources of particles in Cyprus, which may be responsible in part for the high levels reported in this study. Recently, we completed 1 year of particle speciation monitoring in the four largest cities of Cyprus: Nicosia, Limassol, Larnaca, and Paphos. A source apportionment analysis is underway to assess the contributions of local resuspended soil and sea salt particles and their relative importance to local anthropogenic emissions, including traffic, aviation, ships, and industrial sources.

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Implications

This paper examines PM₁₀ concentrations in Nicosia, Cyprus, from 1993 to 2008. The decrease in PM₁₀ levels in Nicosia suggests that the implementation of traffic emission control policies in Cyprus has been effective. However, particle levels still exceeded the European Union annual standard, and dust storms were responsible for a small fraction of the daily PM₁₀ limit exceedances. Other natural particles that are not assessed in this study, such as resuspended soil and sea salt, may be responsible in part for the high particle levels.

Figure 1.
Location of the two measuring sites: Nicosia (urban) and Ayia Marina (background).

Figure 2.

Annual PM₁₀ levels for Nicosia (1993–2008) and Ayia Marina (1999–2008) in µg/m³.

Dashed line shows the EU annual standard of 40 µg/m³ and error bars correspond to the 95% confidence intervals for the dust contribution.

Figure 3. Monthly PM₁₀ concentrations for Nicosia (urban), Ayia Marina (background) and urban contribution in $\mu\text{g}/\text{m}^3$. Error bars correspond to the 95% confidence intervals for the dust contribution.

Figure 4.

Annual PM₁₀ trends adjusted for month, day of week, desert dust storm effect, temperature, wind speed and relative humidity for Nicosia (urban), Ayia Marina (background) and urban contribution. Dashed lines represent the 95% confidence intervals for the estimate.

Figure 5.
Number of observed dust days per year in Cyprus and fitted linear trend (dashed line).

Figure 6. Urban source contributions to PM₁₀ hourly concentrations in the (a) cold and (b) warm season, µg/m³.

PM₁₀ mean daily concentrations during desert dust storms and percent of days exceeding the daily EU limit of 50 µg/m³ at Nicosia and Ayia Marina site for all days and during desert dust storms.

Table 1

Year	Nicosia				Ayia Marina			
	Mean dust PM ₁₀ (µg/m ³)	Exceedance of daily EU limit (50 µg/m ³)		Mean dust PM ₁₀ (µg/m ³)	Exceedance of daily EU limit (50 µg/m ³)		Fraction of exceedances on dust days	
		Percent of days	Fraction of exceedances on dust days		Percent of days	Fraction of exceedances on dust days		
1993	NA *	67.8	NA *					
1994	201.7	54.5	2					
1995	55.5	47.8	1					
1996	470.1	56.8	2					
1997	69.1	63.1	1					
1998	390.9	61.8	2					
1999	80.4	55.8	3	73.8	8.5	3		
2000	127.5	48.5	7	108.3	10.5	6		
2001	100.0	49.3	3	118.0	9.2	5		
2002	98.3	39.0	5	68.1	7.7	5		
2003	121.4	49.7	6	115.2	8.5	6		
2004	115.4	54.8	7	91.5	8.9	6		
2005	116.6	49.3	5	92.6	7.2	5		
2006	185.7	46.1	5	157.9	8.2	5		
2007	93.2	46.5	5	79.9	10.0	6		
2008	117.0	49.4	9	111.9	11.0	9		

Note:

* No dust events were reported or identified for this year.

Table 2Weekday PM₁₀ urban source contributions.

Weekday	PM ₁₀ (µg/m ³)
Sunday	16.4
Monday	25.6
Tuesday	25.4
Wednesday	26.0
Thursday	26.2
Friday	27.6
Saturday	21.3

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