Journal of Toxicology and Environmental Health, Part A: Current Issues
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uteh20

Impact of Sahara Dust Transport on Cape Verde Atmospheric Element Particles

M. Almeida-Silva [a], S. M. Almeida [a], M. C. Freitas [a], C. A. Pio [b], T. Nunes [b] & J. Cardoso [c]
[a] URSN, IST/ITN, Instituto Superior Técnico, Universidade Técnica de Lisboa, Sacavém, Portugal
[b] Aveiro University, CESAM, Aveiro, Portugal
[c] Cape Verde University, Campus do Palmarejo, Praia, Cape Verde
Version of record first published: 20 Mar 2013.

To cite this article: M. Almeida-Silva , S. M. Almeida , M. C. Freitas , C. A. Pio , T. Nunes & J. Cardoso (2013): Impact of Sahara Dust Transport on Cape Verde Atmospheric Element Particles, Journal of Toxicology and Environmental Health, Part A: Current Issues, 76:4-5, 240-251

To link to this article: http://dx.doi.org/10.1080/15287394.2013.757200

Journal of Toxicology and Environmental Health, Part A, 76:240–251, 2013

ISSN: 1528-7394 print / 1087-2620 online
DOI: 10.1080/15287394.2013.757200

Taylor & Francis
Taylor & Francis Group

IMPACT OF SAHARA DUST TRANSPORT ON CAPE VERDE ATMOSPHERIC ELEMENT PARTICLES

M. Almeida-Silva[1], S. M. Almeida[1], M. C. Freitas[1], C. A. Pio[2], T. Nunes[2], J. Cardoso[3]

[1]URSN, IST/ITN, Instituto Superior Técnico, Universidade Técnica de Lisboa, Sacavém, Portugal
[2]Aveiro University, CESAM, Aveiro, Portugal
[3]Cape Verde University, Campus do Palmarejo, Praia, Cape Verde

The objectives of this study were to (1) conduct an elemental characterization of airborne particles sampled in Cape Verde and (2) assess the influence of Sahara desert on local suspended particles. Particulate matter (PM_{10}) was collected in Praia city (14°94′N; 23°49′W) with a low-volume sampler in order to characterize its chemical composition by k_0-INAA. The filter samples were first weighed and subsequently irradiated at the Portuguese Research Reactor. Results showed that PM_{10} concentrations in Cape Verde markedly exceeded the health-based air quality standards defined by the European Union (EU), World Health Organization (WHO), and U.S. Environmental Protection Agency (EPA), in part due to the influence of Sahara dust transport. The PM_{10} composition was characterized essentially by high concentrations of elements originating from the soil (K, Sm, Co, Fe, Sc, Rb, Cr, Ce, and Ba) and sea (Na), and low concentrations of anthropogenic elements (As, Zn, and Sb). In addition, the high concentrations of PM measured in Cape Verde suggest that health of the population may be less affected compared with other sites where PM_{10} concentrations are lower but more enriched with toxic elements.

The Sahara Desert is the most important source of mineral dust, contributing more than 1900 million tons per year (Goudie, 2009; Goudie and Middleton, 2006; Prospero, 1996; D'Almeida, 1986) and responsible for almost half of all the Aeolian material provided to the world's oceans (Miller et al., 2004; Goudie and Middleton, 2001). The most severe dust events globally occur in Sahara Desert (D'Almeida, 1986), which is responsible for the introduction of mineral dust into the atmosphere and transported long distances over the Mediterranean, Europe, North Atlantic Ocean and South America (Remoundaki et al., 2011; Rodríguez et al., 2001; Prospero, 1996; Swap et al., 1992). The Bodélé Depression, located at the southern edge of the Sahara Desert, is considered one of the largest global sources of mineral aerosols due to its unique characteristics (Washington et al., 2006; Prospero et al., 2002). However, other investigators consider the Sahel the major source of mineral dust, attributed to a sequence of 20 dry years that occurred in this area (Prospero, 1996; Mbourou et al., 1996). In the southern Sahara, the contribution of these sources is more frequent during the dry season (November to March) and defined as *Harmattan* (Goudie and Middleton, 2006; Kaufman et al., 2005).

Mineral dust transport has implications on the local, regional, and global climate and environment through the following processes: (1) direct effect on the shortwave and longwave radiating flux through scattering and

We gratefully acknowledge Fundacão para a Ciência e Tecnologia (FCT) for funding M. Almeida-Silva by PhD fellowship (SFRH/BD/69700/2010) and S. M. Almeida by Ciência 2007 programme and the project PTDC/AAC-CLI/100331/2008—*Atmospheric aerosol in Cape Verde region: Seasonal evaluation of composition, sources and transport (CV-Dust)*.

Address correspondence to M. Almeida-Silva, URSN, IST/ITN, Instituto Superior Técnico, Universidade Técnica de Lisboa, Estrada Nacional 10, 2686-953 Sacavém, Portugal. E-mail: marinadealmeidasilva@itn.pt

absorption; (2) indirect influence on radiation budget through interfering in cloud formation; (3) semidirect effect on relative humidity, vertical stability, and precipitation and (4) physical parameters such as visibility (Knippertz and Todd, 2012; Klüser and Holzer-Popp, 2010; Goudie and Middleton, 2006). In addition, it is also important to study the Saharan dust events because they may exert significant effects upon air quality and, consequently, on human health and well-being (Goudie, 2009; Samet and Krewski, 2007; Cohen et al., 2005; Krewski et al., 2004; Pope et al., 2002).

Several epidemiological studies showed an association between air PM and an increase in morbidity and rate of mortality (Cohen et al., 2005; Krewski et al., 2004; Pope et al., 2002). However, the impact of Sahara dust events on human health is not well documented, and the findings are inconsistent. Studies developed in Greece, Italy, and Spain revealed an increase on adverse respiratory syndromes and higher daily mortality rate during Saharan dust events (Nastos et al., 2011; Sajani et al., 2010; Perez et al., 2008). In addition, several investigators demonstrated that PM-induced adverse health effects depend not only on PM mass concentration, but also on size and chemical composition (Valavanidis et al., 2008).

Epidemiologic data support the hypothesis that coarse particles derived from natural sources may be less toxic than particles generated by combustion processes and, consequently, are associated with fewer human health illnesses (Fromme et al., 2008; Janssen et al., 2005). It is also well known that Saharan dust is characterized by coarse particles with Earth crustal material in their composition. For this reason, further investigations are determining whether Saharan dust concentration has human health consequences.

The objectives of this study were to (1) conduct an elemental characterization of airborne particles sampled in Cape Verde and (2) assess the influence of Sahara Desert dust on composition of local suspended particles. This study was performed within the ongoing project *Atmospheric aerosol in Cape Verde region: Seasonal evaluation of composition, sources and transport (CV-Dust)*, which aims to assess transport of dust from Sahara Desert by using an integration of measuring and modeling tools.

MATERIALS AND METHODS

Sampling

This study was carried out in Santiago's island, the largest island of Cape Verde Archipelago. Cape Verde is an archipelago composed of 10 islands, located offshore of Western Africa coast. Santiago's island has an area of 991 km^2 (Figure 1), and more than 200,000 inhabitants. The localization is directly on the route of Saharan dust transport to the Atlantic Ocean, and thus an ideal place to quantify and characterize the African aeolian aerosol.

One Tecora sampler, which is a low-volume particle sampler, operating at an average flow rate of 16.3 L/min^1, was installed in Praia city (14°94'N; 23°49'W) during the year 2011. The sampler collected PM with an aerodynamic diameter lower than 10 μm (PM_{10}), on Nuclepore polycarbonate filters with a diameter of 47 mm, in order to characterize their chemical composition. The sampling time ranged between 6 to 96 h, decreasing during Saharan dust episodes. Therefore, the average values presented in this study are considered according to the sampling time of each filter.

Chemical Analysis—INAA

The collected filters were weighed in a controlled clean room (class 10,000) at 20 ± 1°C and 50 ± 5% relative humidity, and filters were kept for 24 h in the same environment to equilibrate before weighing (EN12341:1998). Filter mass before and after sampling was obtained as the mean of three measurements, when observed variations were less than 1%. One quarter of the filters were rolled up, put into aluminum foil, and irradiated at the Portuguese Research Reactor (RPI-ITN; nominal power: 1 MW) for 5 h. After the irradiation, filters were removed from the aluminum foil and inserted in polyethylene containers; samples were measured for 5–7 h, 2–5 d, and 4 wk in a high-purity and high-resolution germanium

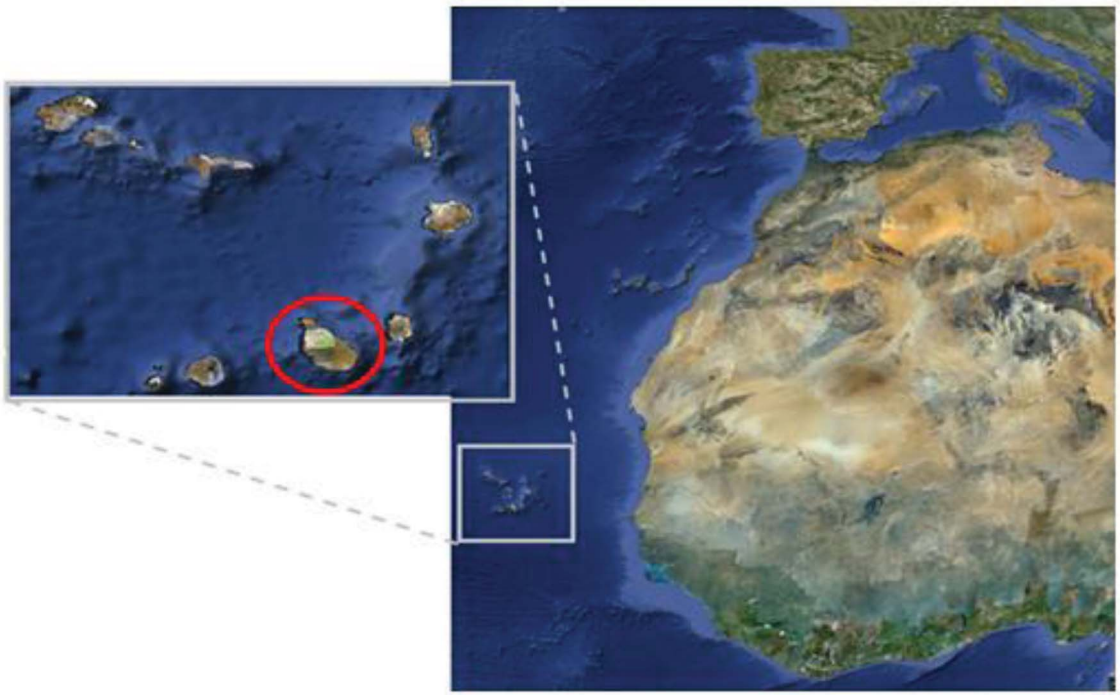

FIGURE 1. Localization of the Cape Verde Islands (color figure available online).

detector, with an ORTEC automatic sampler changer, in order to determine several natural and anthropogenic elements including Ba, Ce, Co, Cr, Fe, K, Na, Rb, Sc, Sm, As, Sb, and Zn, respectively. For comparison, Al–0.1% Au alloy disk with a thickness of 125 μm and a diameter of 0.5 cm was co-irradiated with the samples for the application of the k_0-INAA methodology (De Corte, 1987).

Quality control was ensured with the use of 20–30 mg of the reference material NIST-SRM 1633a "Coal Fly Ash." The reference material was co-irradiated with each batch of samples and measured, for 60 min after 2–5 d and 4 wk of decay, in the same detector. The agreement was reliable, with deviations from certified and consensus elements (Roelandts and Gladney, 1998) below 15%. All results obtained in were considered for 1 yr of sampling campaign to allow for comparison with standard values.

Data Analysis

Correlation between aerosols constituents were assessed by means of a Pearson correlation, considering 95% of confidence level and using the STATISTICA software. Enrichment factor (EF) analysis is a tool that could be used to evaluate the strength of the crustal and noncrustal origin of the elements. Enrichment factors, using Fe as a crustal reference element (EF_{Fe}), were calculated based on Eq. (1) and using Saharan dust composition determined by (Reguigui et al., 2002):

$$EF_{Fe} = \frac{([X]/[Fe])\,air}{([X]/[Fe])\,soil} \quad (1)$$

If the estimated value for EF_{Fe} is approximately 1, the dominant source is the soil. In contrast, the anthropogenic sources are dominant for estimated values higher than 1. An equivalent formulation could be used to assess other aerosol source contribution, since a reference element and average chemical composition are known for a specific source.

Air Mass Back Trajectories—HYSPLIT Model

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model was used to perform 3-day backward trajectories, ending in Santiago Island. The software was

run for each sample at 1000 m height, starting a new trajectory every 24 h, and using the vertical velocity option.

RESULTS AND DISCUSSION

PM_{10} Concentration

Figure 2 presents the seasonal variation of the PM_{10} concentrations measured during the sampling campaign performed in 2011 and shows that the highest PM_{10} values were registered for the dry months: December to March. This is in agreement with Goudie and Middleton (2006), who suggested that in the south of the Sahara Desert the higher number of days with blowing dust/sand occur between November and March. A recent study developed in Canary Islands showed that the most intense dust events occurred during the dry season, between December to March, and reached a total suspended particles concentration of 5586 $\mu g/m^3$ (Gelado-Caballero et al., 2012). This dry period is typically named *Harmattan* (Simonson, 1995). The PM_{10} mean concentration measured during the sampling campaign was 60 $\mu g/m^3$. This concentration is above (1) the annual PM_{10} limit value of 40 $\mu g/m^3$ defined by the European Directive 2008/50/EC (EU, 2008), (2) the World Health Organization PM_{10} annual standard of 20 $\mu g/m^3$ (World Health Organization, 2000), and (3) the U.S. Environmental Protection Agency health-based air quality PM_{10} annual standard of 50 $\mu g/m^3$.

PM_{10} Element Characterization

INAA was used in order to determine the chemical elements in PM_{10}. Figure 2 presents the mass concentration for the measured elements and demonstrates that As, Ba, Sm, Ce, Cr, Co, Fe, K, and Sc presented a similar behavior throughout the sampling period. This seasonal trend is also comparable with seasonal variation of PM_{10} evidenced by two high peaks in February 2011. The element As showed an additional peak in September and an average throughout the sampling campaign of 0.5 ng m^{-3}. This value does not exceed the annual arsenic limit value of 6 ng m^{-3}, defined by the European Directive 2004/107/EC (EU, 2004).

Table 1 presents the Pearson correlation coefficients for the total PM_{10} and element mass concentration. The coefficients with statistical significance at 95% confidence level are shown in bold. Results confirmed that referred elements are correlated, suggesting their association with a common source, which is probably the soil. The elements Na, Zn, and Sb did not present a correlation, neither with previous elements nor between themselves. This finding indicates their origin from other sources, probably sea salt for Na and anthropogenic emissions for Zn and Sb (Almeida et al., 2005; 2006a).

Table 2 aimed to compare PM_{10} total and element concentrations measured in Cape Verde with the concentrations measured in other sites of the globe. Results showed that PM_{10} concentrations in Cape Verde were higher than concentrations measured in Europe and America, but lower than the concentrations measured in a suburban area in Ghana (Aboh et al., 2009); in Agra (India), which is bounded by the Thar Desert of Rajasthan (Kulshrestha et al., 2009); and in Hangzhou, an industrialized and urbanized region (Cao et al., 2009). A similar behavior was found for Fe. This element is commonly associated with soil, and therefore it was expected there would be a link between the highest concentrations and the sites characterized by dry climates and urban areas where resuspension of the road dust is a significant source.

Sodium concentrations in Cape Verde presented the highest concentrations, and this is concordant with the geographical position of the island, where sea salt is the predominant source of Na in atmospheric aerosols. Potassium concentrations were higher in Cape Verde compared with concentrations measured in Europe and America but lower than concentrations measured in Pakistan, Ghana, and China (von Schneidemesser et al., 2010; Aboh et al., 2009; Cao et al., 2009). Almeida and coworkers (2006b) indicated this element is associated with soil (insoluble coarse fraction),

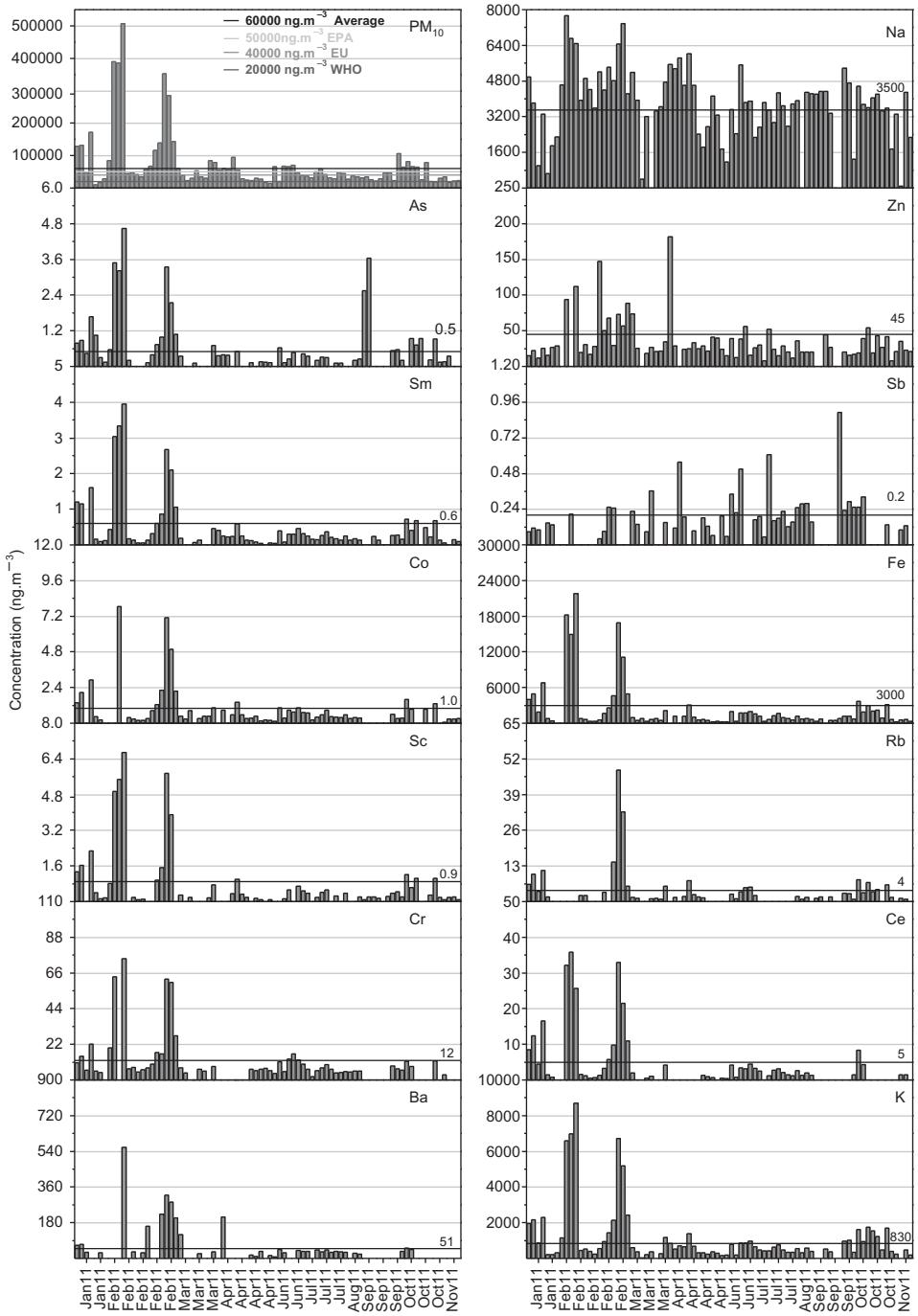

FIGURE 2. Seasonal variation of PM_{10} mass and element concentrations (ng.m^{-3}). The black line shows the average value for each element.

sea (soluble coarse fraction), and combustion (fine fraction), a common tracer of biomass burning (Mkoma et al., 2009). The higher concentrations of this element measured in the Cape Verde are explained by the fact that the natural sources (soil and sea) are predominant in the island. K-feldspar is ubiquitous in mineral dust. The probable influence of the biomass burning from the African Continent needs to be studied further.

TABLE 1. Pearson Correlation Coefficients of all the Chemical Elements Determined

	PM_{10}	K	Na	As	Zn	Sm	Sb	Co	Fe	Sc	Rb	Cr	Ce	Ba
PM_{10}	**1.00**	**0.99**	0.63	**0.82**	0.48	**0.99**	−0.01	**0.98**	**0.99**	**0.99**	**0.95**	**0.97**	**0.96**	**0.92**
K		**1.00**	0.62	**0.98**	0.45	**0.99**	0.02	**0.98**	**0.99**	**0.99**	**0.97**	**0.98**	**0.96**	**0.90**
Na			**1.00**	0.51	0.46	0.60	0.27	0.51	0.58	0.62	0.49	0.65	0.65	0.69
As				**1.00**	0.39	**0.98**	0.00	**0.97**	**0.83**	**0.82**	0.58	**0.95**	**0.94**	**0.90**
Zn					**1.00**	0.43	0.04	0.30	0.55	0.74	0.44	0.60	0.49	0.68
Sm						**1.00**	−0.01	**0.98**	**0.99**	**0.99**	**0.92**	**0.95**	**0.97**	**0.89**
Sb							**1.00**	0.05	0.00	−0.06	−0.07	0.19	0.02	−0.10
Co								**1.00**	**0.99**	**0.99**	**0.98**	**0.96**	**0.99**	**0.82**
Fe									**1.00**	**0.99**	**0.97**	**0.97**	**0.96**	**0.90**
Sc										**1.00**	**0.98**	**0.98**	**0.97**	**0.94**
Rb											**1.00**	**0.95**	**0.95**	0.79
Cr												**1.00**	**0.94**	**0.93**
Ce													**1.00**	**0.85**
Ba														**1.00**

Note. Values in shadowed boldface have a positive correlation statistically significant at 95% confidence level.

For the elements As, Sb, and Zn an opposite behavior was observed with concentrations lower in Cape Verde compared with other referred sites. These elements are associated with anthropogenic sources, as combustion processes, vehicle exhaust, and industrial processes (Almeida et al., 2005).

Enrichment factors, presented in Figure 3, showed the strength of the crustal and noncrustal sources for each measured element. The lower enrichment factors, related to Fe, were observed for the elements Ba, Sm, Ce, Rb, K, and Sc. Figure 4 presents the relationship between these elements with Fe and the lines indicate the soil composition provided from two different references: One corresponds to a general composition of the soil (Mason and Moore, 1982) and the other is related to a Saharan soil (Reguigui et al., 2002). Results not only showed a strong correlation between the referred elements but also indicated an association between these elements in the aerosol and the soil composition. Na, Zn, and Sb presented higher enrichment factors related to the soil, denoting the influence of other sources. However, the enrichment factors obtained for the elements As, Sb, and Zn in Cape Verde were significantly lower compared with other studies performed in Europe, and a study performed in Lisbon, Portugal, registered enrichment factors of 110, 2900, and 140 for As, Sb, and Zn, respectively (Almeida et al., 2005).

Influence of Sahara dust on Cape Verde Aerosol

The HYSPLIT model was run for 72 h before each sample, in order to identify the origin of the air masses that affected the region during the sampling campaign. Results showed that the episodes of air mass transport from the Sahara Desert, identified by the model, were associated with the highest concentrations of PM_{10} and with the identified crustal components. Figure 5 shows that the air mass trajectories associated with the two peaks, which occurred in February, crossed through the Sahara Desert. The Saharan transport event that occurred on February 5 and 28 resulted in highest concentrations for PM_{10}, Fe, K, Sc, and Sm of 507,000 ng/m^3, 21,800 ng/m^3, 8700 ng/m^3, 6.7 ng/m^3, and 3.9 ng/m^3, respectively (when the average concentration was 60,000 ng/m^3, 3000 n/m^3, 830 ng/m^3, 0.9 ng/m^3, and 0.6 ng/m^3, respectively).

CONCLUSIONS

In this study an element characterization of the Cape Verde aerosol was performed. The main conclusions may be summarized as follows:

- A seasonality in the PM_{10} concentrations characterized by higher concentrations in the dry season was observed.

TABLE 2. Average Concentrations of Some Chemical Elements in Different Places in the Whole World

Country/city	Type of region	PM_{10}	As	Fe	K	Na	Sb	Zn
This work	Urban	60	0.5	3000	830	3500	0.2	45
Europe								
Spain/Pamplona (Aldabe et al., 2011)	Urban	26	—	414	759	2604	—	—
Spain/Pamplona (Aldabe et al., 2011)	Traffic	28	—	440	210	570	2.3	80
Spain/Bertiz (Aldabe et al., 2011)	Rural	15	—	330	130	520	—	—
Spain/Santander (Arruti et al., 2011)	Urban	29[a], 28[b]	—	90	150	610	—	—
Spain/Los Tojos (Arruti et al., 2011)	Rural	30[a], 31[b]	0.4	100	200	1800	—	—
Spain/Huelva (de la Campa et al., 2011)	Urban	38	0.04	30	500	400	—	—
France/Dunkirk (Alleman et al., 2010)	Industrial	—	5.1	977	674	1550	2.3	80
Turkey, Istanbul (Theodosi et al., 2010)	Urban		—	700	710[c]	2690[d]	—	240
Portugal, Lisbon (Farinha et al., 2009)	Suburban		0.2	305	172	1070	1.9	46
Greece/Athens (Karanasiou et al., 2009)	Urban	54	—	414	759	2604	—	—
Austria, Vienna (Limbeck et al., 2009)	Traffic	33	1.2	740	—	—	3.3	48
Austria, Vienna (Limbeck et al., 2009)	Urban	28	0.9	780	—	—	2.5	40
Austria, Vienna (Limbeck et al., 2009)	Background	20	0.7	250	—	—	1.5	27
Turkey, Istanbul (Koçak et al., 2007)	Rural	27	—	298	244[c]	3095[d]	—	5
Portugal, Lisbon (Almeida et al., 2006)	Suburban	40	0.4	400	270	1500	2.6	36
Africa								
Nigeria, Ikoyi Lagos (Ezeh et al., 2012)	Suburban	—	—	892	850	—	—	58
Tanzania, Morogoro (Mkoma et al., 2009)	Residential	23	<1.0	610	470	410[4]	—	6
Tanzania, Dar es Salaam (Mkoma et al., 2009)	Urban	46	1.2	410	620	1570[4]	—	370
Ghana, Accra (Aboh et al., 2009)	Suburban	138	—	4170	1650	—	—	21
Zimbabwe, Rukomechi (Nyanganyura et al., 2007)	Semiarid	9	—	266	138	321	—	1
Asia								
Tibet, Lahsa (Cong et al., 2011)	Urban	52	1.8	1034	614	345		81
Pakistan, Lahore (von Schneidemesser et al., 2010)	Urban	–	22	8200	5600	1900	66	11,000
India, Agra (Kulshrestha et al., 2009)	Urban	154	—	2900	—	—	—	500
India, Agra (Kulshrestha et al., 2009)	Rural	148	—	3200	—	—	—	1600
China, Hangzhou (Cao et al., 2009)	Urban	119	120	2190	4160	1150	—	550
America								
Costa Rica, San José (Herrera et al., 2009)	Urban	47	—	509	290[3]	750[4]		
USA, Phoenix (Upadhyay et al., 2011)	Urban	42	1	1088	633	—	3.1	37
USA, Los Angeles (Pakbin et al., 2011)	Urban	11	—	322	79	570	2.1	6
Brazil, Rio de Janeiro (Gioda et al., 2011)	Urban	47	—	810	350	2760	—	6140

[a] 2008.
[b] 2009.
[c] The value corresponds to K^+.
[d] The value corresponds to Na^+.

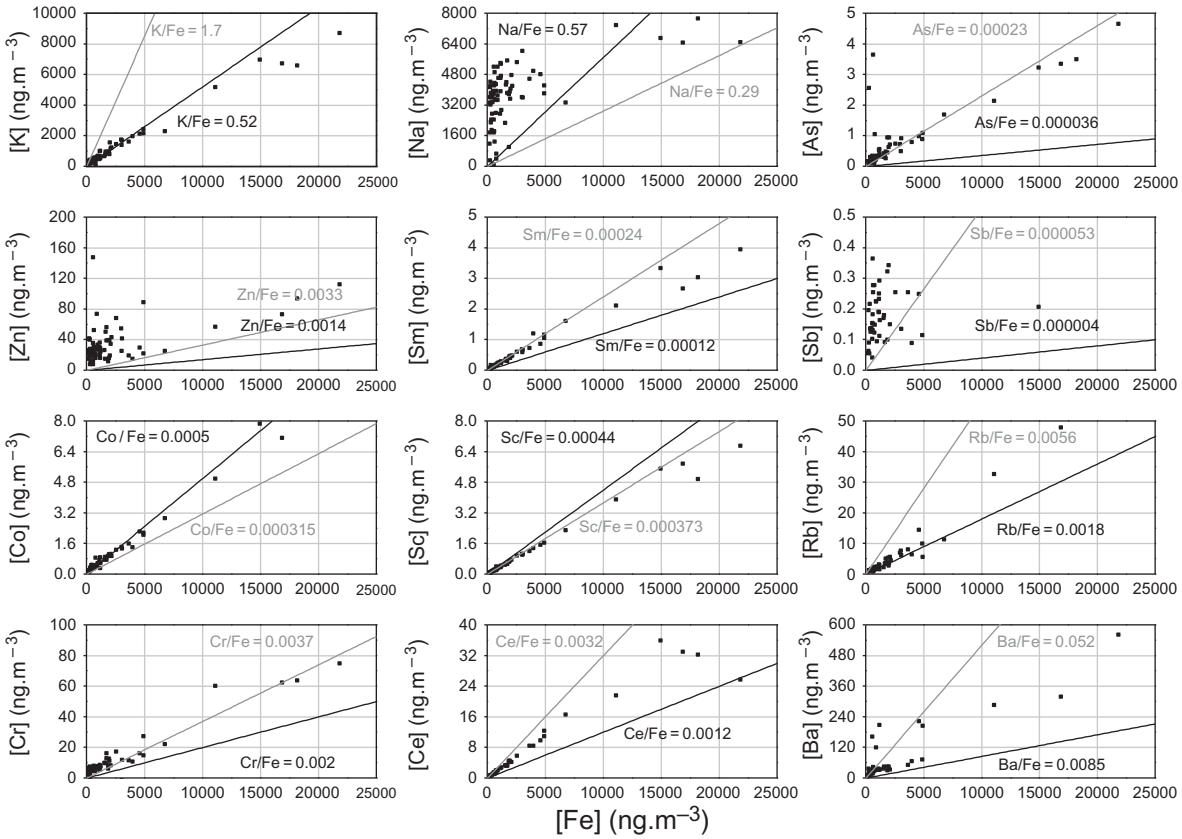

FIGURE 3. Enrichment factor using Fe as a reference element and (Reguigui, Kucera, & Kraiem, 2002) Sahara soil composition. The vertical bars are the Standard Deviation.

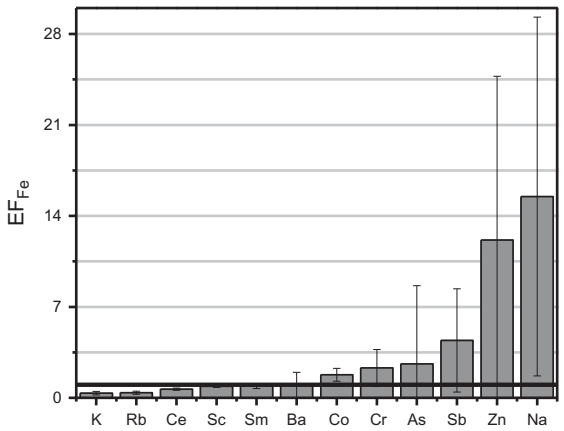

FIGURE 4. Relation between PM_{10} composition and different types of soil. (—— Sahara Desert soil (Reguigui, Kucera, & Kraiem, 2002); —— soil Mason composition (Mason & Moore, 1982)).

- PM_{10} concentration in Cape Verde markedly exceeded the health-based air quality standards defined by the European Union (EU), World Health Organization (WHO), and U.S. Environmental Protection Agency (EPA).
- Cape Verde PM_{10} composition is characterized essentially by high concentrations of elements originating from soil (Fe, Ba, Sm, Ce, K, and Sc) and sea (Na); and low concentrations of anthropogenic elements (As, Sb, and Zn).
- The analysis of the air mass trajectories indicated a high contribution of Sahara dust to the Cape Verde aerosol.
- The results obtained in this study support the notion that Cape Verde aerosol impacts population health due to its high concentrations of PM. However, the study of the aerosol composition suggested that these high concentrations are mainly associated with natural sources that are principally related with the coarse fraction of the aerosol, which exerts less respiratory penetration rates, and with emission of lower toxic species. Therefore,

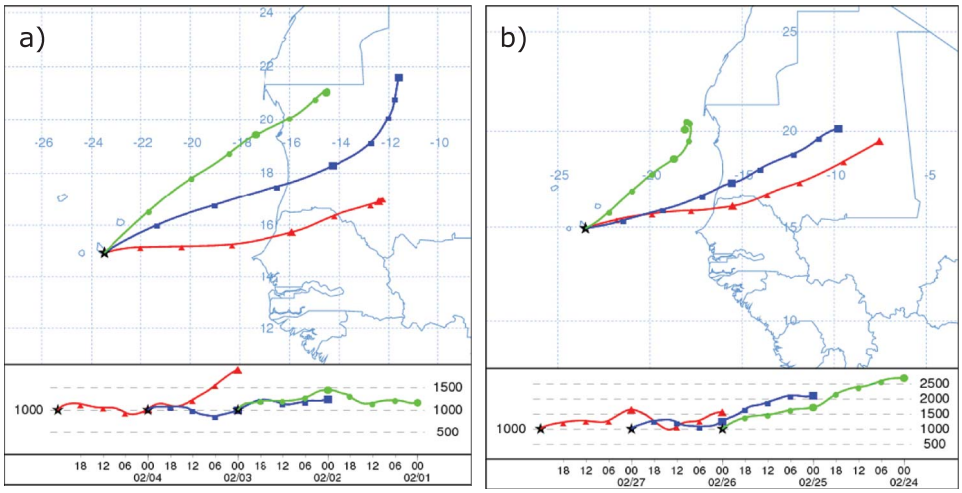

FIGURE 5. Hysplit model backward trajectories for 5th February (a) and 28th February (b) 2011 (color figure available online).

further studies need to assess the strength of the impact of the Cape Verde aerosol on human well-being.

REFERENCES

Aboh, I., Henriksson, D., Laursen, J., Lundin, M., Ofosu, F., Pind, N., Lingren, E. S., and Wahnstrom, T. 2009. Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques. *X-Ray Spectrom*. 38: 348–353.

Aldabe, J., Elustondo, D., Santamaría, C., Lasheras, E., Pandolfi, M., Alastuey, A., Qerol, X., and Santamaría, J. M. 2011. Chemical characterisation and source apportionment of PM2.5 and PM10 at rural, urban and traffic sites in Navarra (North of Spain). *Atmos. Res*. 102: 191–205.

Alleman, L., Lamaison, L., Perdrix, E., Robache, A., and Galloo, J. 2010. PM10 metal concentrations and source identification using positive matrix factorization and wind sectoring in a French industrial zone. *Atmos. Res*. 96: 612–625.

Almeida, S., Pio, C., Freitas, M., Reis, M., and Transcoso, M. 2006a. Source apportionment of atmospheric urban aerosol based on weekdays/weekend variability: Evaluation of road re-suspended dust contribution. *Atmos. Environ*. 40: 2058–2067.

Almeida, S., Freitas, M., Reis, M., Pio, C., and Trancoso, M. 2006b. Combined application of multielement analysis—k0-INAA and PIXE—and classical techniques for source apportionment in aerosol studies. *Nucl. Instrum. Methods Phys. Res. A* 564: 752–760.

Almeida, S., Pio, C., Freitas, M., Reis, M., and Transcoso, M. 2005. Source apportionment of fine and coarse particulate matter in a sub-urban area at the Western European Coast. *Atmos. Environ* 39: 3127–3138.

Arruti, A., Fernandéz-Olmo, I., and Irabien, A. 2011. Regional evaluation of particulate matter composition in an Atlantic coastal area (Cantabria region, northern Spain): Spatial variations in different urban and rural environments. *Atmos. Res*. 101: 280–293.

Cao, J., Shen, Z., Chow, J., Qi, G., and Watson, J. 2009. Seasonal variations and sources of mass and chemical composition for PM10 aerosol in Hangzhou, China. *Particuology* 7: 161–168.

Cohen, A. J., Anderson, H. R., Ostra, B., Pandey, K. D., Krzyzanowski, M., Kunzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M., and Smith, K. 2005. The global burden of disease due to outdoor air pollution. *J. Toxicol. Environ. Health A* 68: 1–7.

Cong, Z., Kang, S., Chunling, L., Li, Q., Huang, J., Gao, S., and Li, X. 2011. Trace

elements and lead isotopic composition of PM10 in Lhasa, Tibet. *Atmos. Environ*. 45: 6210–6215.

D'Almeida, G. 1986. A model for Saharan dust transport. *J. Climate Appl. Meteorol*. 25: 903–916.

De Corte, F. 1987. *The k0-standardization method—A move to the optimization of neutron activation analysis*. Aggregé thesis, Gent University, Gent, Belgium.

de la Campa, A. M. S., de la Rosa, J., González-Castanedo, Y., Férnandez-Camacho, R., Alastuey, A., Qerol, X., Stein, A. F., Ramos, J. L., Radríguez, S., Garcís Orelana, I., and Nava, S. 2011. Levels and chemical composition of PM in a city near a large Cu-smelter in Spain. *J. Environ. Monitor*. 13: 1276–1287.

EN 12341. 1998. Air quality-determination of the PM10 fraction of suspended particulate matter. Reference method and field test procedure to demonstrate reference equivalence of measurement methods. Available at http://www.standardsdirect.org/

European Parliament and of the Council. 2004. Directive 2008/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. Available at http://eur-lex.europa.eu/

European Parliament and of the Council. 2008. Directive 2008/50/EC on ambient air quality and cleaner air for Europe. Available at http://eur-lex.europa.eu/

Ezeh, G., Obioh, I., Asubiojo, O., and Abiye, O. 2012. PIXE characterization of PM10 and PM2.5 particulates sizes collected in Ikoyi Lagos, Nigeria. *Toxicol. Environ. Chem*. 5: 884–894.

Farinha, M., Almeida, S., Freitas, M., Verburg, T., and Wolterbeek, H. 2009. Local and regional sources of air pollutants at Northern Lisbon area, Portugal. *Appl. Radiat. Isotopes* 67: 2137–2141.

Fromme, H., Diemer, J., Dietrich, S., Cyrys, J., Heinrich, J., Lang, W., Kiranoglu, M., and Twardella, D. 2008. Chemical and morphological properties of particulate matter (PM10, PM2.5) in school classrooms and outdoor air. *Atmos. Environ*. 42: 6597–6605.

Gelado-Caballero, M., López-Garcia, P., Prieto, S., Patey, M., Collado, C., and Hérnández-Brito, J. 2012. Long-term aerosol measurments in Grand Canaria, Canary Islands: Particle concentration, sources and elemental composition. *J. Geophys. Res*. 117: 3304–3319.

Gioda, A., Amaral, B., Monteiro, I., and Saint'Pierre, T. 2011. Chemical composition, sources, solubility, and transport of aerosol trace elements in a tropical region. *J. Environ. Monitor*. 13: 2134–2142.

Goudie, A. 2009. Dust storms: Recent developments. *J. Environ. Manage*. 90: 89–94.

Goudie, A., and Middleton, N. 2001. Saharan dust storms: Nature and consequences. *Earth-Sci. Rev*. 56: 179–204.

Goudie, A., and Middleton, N. 2006. *Desert dust in the global system*. Heidelberg, Germany: Springer.

Herrera, J., Rodriguez, S., and Baez, A. 2009. Chemical composition and sources of PM10 particulate matter collected in San José, Costa Rica. *Atmos. Sci*. J. 3: 124–130.

Janssen, N. A. H., Lanki, T., Hoek, G., Vallius, M., de Hartog, J. J., Van Grieken, R., Pekkanen, J., Brunekreef, B. 2005. Associations between ambient, personal, and indoor exposure to fine particulate matter constituents in Dutch and Finnish panels of cardiovascular patients. *Occup. Environ. Med*. 62: 868–877.

Karanasiou, A., Siskos, P., and Eleftheriadis, K. 2009. Assessment of source apportionment by positive matrix factorization analysis on fine and coarse urban aerosol size fractions. *Atmos. Environ*. 43: 3385–3395.

Kaufman, Y., Joren, I., Remer, L., Tanré, D., Ginoux, P., and Fan, S. 2005. Dust transport and deposition observed from the Terra-MODIS spacecraft over the Atlantic Ocean. *J. Geophys. Res*. 110: 16.

Klüser, L., and Holzer-Popp, T. 2010. Relationship between mineral dust and cloud properties in the West African Sahel. *Atmos. Chem. Phys*. 10: 6901–6915.

Knippertz, P., and Todd, M. 2012. Mineral dust aerosols over the Sahara: Meteorological

controls on emission and transport and implications for modeling. *Rev. Geophys*. 50: 1–28.

Krewski, D., Burnett, R. T., Jerrett, M., Pope, A., Rainham, D. G., Calle, E. E., Thurston, G. D., and Thun, M. 2004. Mortality and long-term exposure to ambient air pollution: Ongoing analyses based on the American Cancer Society cohort. *J. Toxicol. Environ. Health A* 68: 1093–1109.

Koçak, M., Mihalopoulos, N., and Kubilay, N. 2007. Chemical composition of the fine and coarse fraction of aerosols in the northeastern Mediterranean. *Atmos. Environ*. 41: 7351–7368.

Kulshrestha, A., Satsangi, P., Masih, J., and Taneja, A. 2009. Metal concentration of PM2.5 and PM10 particles and seasonal variations in urban and rural environment of Agra, India. *Sci. Total Environ*. 407: 6196–6204.

Limbeck, A., Handler, M., Puls, C., Zbiral, J., Bauer, H., and Puxbaum, H. 2009. Impact of mineral components and selected trace elements on ambient PM10 concentrations. *Atmos. Environ*. 43: 530–538.

Mason, B., and Moore, C. 1982. *Principles of geochemistry*. 46. New York, NY: Wiley.

Mbourou, G., Bertrand, J., and Nicholson, S. 1996. The diurnal and seasonal cycles of wind-borne dust over Africa north of the Equator. *J. Appl. Meteorol*. 36: 868–882.

Miller, R., Tegen, I., and Perlwitz, J. 2004. Surface radiative forcing by soil dust aerosols and hydrologic cycle. *J. Geophys. Res*. 109D.

Mkoma, S., Wang, W., and Maenhaut, W. 2009b. Seasonal variation of water-soluble inorganic species in the coarse and fine atmospheric aerosols at Dar es Salaam, Tanzania. *Nucl. Instrum. Methods Phys. Res. B* 267: 2897–2902.

Nastos, P. T., Giaouzaki, K. N., Kampanis, N. A., Agouridakis, P. I., and Matzarakis, A. 2011. Environmental impacts on human health during a Saharan dust episode at Crete Island, Greece. *Meteorol. Z*. 20: 517–529.

Nyanganyura, D., Maenhaut, W., Mathuthu, M., Makarau, A., and Meixner, F. 2007. The chemical composition of tropospheric aerosols and their contributing sources to a continental background site in northern Zimbabwe from 1994 to 2000. *Atmos. Environ*. 41: 2644–2659.

Pakbin, P., Ning, Z., Shafer, M., Schauer, J., and Sioutas, C. 2011. Seasonal and spatial coarse particle elemental concentrations in the Los Angeles area. *Aerosol Sci. Technol*. 45: 949–963.

Perez, L., Aurelio, T., Querol, X., Künzli, N., Pey, J., Alastuey, A., et al. 2008. Coarse particles from Saharan dust and daily mortality. *Epidemiology* 19: 800–807.

Pope, C., Burnett, R., Thun, M., Calle, E., Frewski, D., Ito, K., and Thurston, G. D. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J. Am. Med. Assoc*. 28: 1132–1141.

Prospero, J. 1996. *Saharan dust transport over the North Atlantic Ocean and Mediterranean: An overview*, 133–151.Dordrecht, The Netherlands: Kluwer Academic Publishers, The Netherlands.

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E. 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys*. 40: 1–31.

Reguigui, N., Kucera, J., and Kraiem, H. 2002. Determination of trace elements in Tunisian soil, desert and beach sand using instrumental neutron activation analysis. *Proc. Int. Symp. Environ. Pollut. Control Waste Manage*., 70–82.

Remoundaki, E., Bourliva, A., Kokkalis, P., Mamouri, R. E., Papayannis, A., Grigoratos, T., Samara, C., and Tsezos, M. 2011. PM10 composition during an intense Saharan dust transport event over Athens (Greece). *Sci. Total Environ*. 409: 4361–4372.

Rodríguez, S., Querol, X., Alastuey, A., Kallos, G., and Kakaliagou, O. 2001. Saharan dust contributions to PM10 and TSP levels in Sourthern and Eastern Spain. *Atmos. Environ*. 35: 2433–2447.

Roelandts, I., and Gladney, E. 1998. Consensus values for NIST biological and environmental

standard reference materials. *Fres. J. Anal. Chem*. 360: 327–338.

Sajani, S. Z., Miglio, R., Bonasoni, P., Cristofanelli, P., Marinoni, A., Sartini, C., Goldoni, C. A., Girolamo, G., and Lauriola, P. 2010. Saharan dust and daily mortality in Emilia-Romagna (Italy). *Occup. Environ. Med*. 68: 446–451.

Samet, J., and Krewski, D. 2007. Health effects associated with exposure to ambient air pollution. *J. Toxicol. Environ. Health A* 70: 227–242.

Simonson, R. 1995. Airborne dust and its significance to soils. *Geoderma* 65: 1–43.

Swap, R., Garstang, M., and Greco, S. 1992. Saharan dust in Amazon Basin. *Tellus* 44B: 133–149.

Theodosi, C., Im, U., Bougiatioti, A., Zarmpas, P., Yenigun, P., and Mihalopoulos, N. 2010. Aerosol chemical composition over Istanbul. *Sci. Total Environ*. 408: 2482–2491.

Upadhyay, N., Clements, A., Fraser, M., and Herckes, P. 2011. Chemical speciation of PM2.5 and PM10 in South Phoenix, AZ. *J. Air Waste Manage. Assoc*. 61: 302–310.

US Environmental Protection Agency. 2008. *Clean air act; 2008*. Available at https://www.epa.gov.

Valavanidis, A., Fiotakis, K., and Vlachogianni, T. 2008. Airborne particulate matter and human health: Toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *J. Environ. Sci. Health Part C* 26: 339–362.

von Schneidemesser, E., Stone, E., Quraishi, T., Shafer, M., and Schauer, J. 2010. Toxic metals in the atmospheric in Lahore, Pakistan. *Sci. Total Environ*. 408: 1640–1648.

Washington, R., Todd, M., Engelstaedter, S., Mbainayel, S., and Mitchell, F. 2006. Dust and the low-level circulation over the Bodélé Depression, Chad: Observations from BoDEx 2005. *J. Geophys. Res*. 111: 1–15.

World Health Organization. 2000. *Air quality guidelines for Europe*. Copenhagen: WHO Regional Publications number 91.