Seasonal Variation of Atmospheric Composition of Water-Soluble Inorganic Species at Rural Background Site in Tanzania, East Africa

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Abstract

Samples of coarse, fine and PM10 aerosols were collected at a rural Morogoro sites, during the 2005 dry season and 2006 wet season campaigns using a "Gent" PM10 stacked filter unit sampler with sequential Nuclepore polycarbonate filters. A total of 80 aerosol samples were analyzed for water-soluble inorganic ions components using Ion Chromatography. The mean concentration for the anions Cl^-, NO_3^-, *and* SO_4^{2-} *and the cations* Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, *showed seasonal variation in all size fractions with higher levels during the 2005 dry season campaign than the 2006 wet season campaign. The mean concentrations and associated standard deviation of fine, coarse and PM10 mass were, 17±4, 52±27 and 69±29* $\mu g/m^3$ *during the 2005 dry season campaign and 13±5, 34±23 and 47±25* $\mu g/m^3$ *for the 2006 wet season campaign, respectively.* Ca^{2+} *was the most important cation and the* SO_4^{2-} *was the main acidifying anionic component in PM10 while* NH_4^+ *was the most abundant cation in the fine fraction and* Cl^- *the main anionic species in the coarse fraction. The ion balance ratios were all larger than 1.0; they range from 1.30 to 1.44 for the fine fraction and from 2.01 to 3.14 for the coarse fraction. The carbonates were not measured by Ion Chromatography therefore; these missing carbonates are thought to be largely responsible for the observed deviation from 1.0. The study suggests that primary sources such as soil dust dispersion and biomass burning made a significant contribution to the atmospheric particulate pollution in Morogoro.*

Keywords: Ion chromatography; Aerosol Characterization; coarse, fine and PM10 fractions; Meteorology

Introduction

There is an increasing awareness of the influence of ambient particulate matter (PM) on environmental systems and human health. Atmospheric particles may greatly vary in their size, chemical composition, and temporal and spatial variations. Among the suspended particles in ambient air, atmospheric particulate matter with an aerodynamic diameter less than 10 µm (PM10), and especially the fine particle fraction with aerodynamic diameter less than 2.5 µm (PM2.5) are of considerable concern. The chemical composition of PM10 and PM2.5 is critically important to gain insights into sources and their atmospheric formation pathways and of their toxicity and to evaluate the effectiveness of abatement strategies for relevant emission sectors (Harrison et al., 2004; Tippayawong, et al., 2006; Giri, et al., 2006).

The major inorganic ions components of PM2.5 are reported to be sulphate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) (Turnbull and Harrison, 2000; Lee and Kang, 2001) and are associated with atmospheric visibility degradation, adverse human health effects, and acidity of precipitation (Dockery and Pope, 1996; Pope et al., 2002; Watson, 2002; Villeneuve et al., 2003; IPCC, 2007). Ion chromatography (IC) is widely used for the measurement of inorganic ions in particles since it offers advantages in terms of sensitivity and multiple analyte determination in a single assay (McMurry, 2000; Wilson et al., 2002).

So far, only a few aerosol measurements are available for Tanzania (Koleleni, 2002; Bennet et al., 2005; Msafiri, 2005) and particularly in Morogoro (Mkoma et al., 2009a,b). In this study, ion chromatography (IC) in conjunction with ultrasonic extraction was employed for the characterisation of water-soluble inorganic ions in PM10-2, PM2 (hereafter referred to as coarse and fine particles) and total PM10 aerosols at a rural site in Morogoro, Tanzania. The influences of meteorology on PM and ions levels are reported and in addition the ionic balance and the seasonal variations of the water-soluble ions in different size fractions have been discussed.

Materials and Methods

The sampling campaign at rural Morogoro took place between July 2005 and April 2006. The site is located at 6°49'39.7"S, 37°39'48.1"E, altitude 526 m a.s.l, and is at about 200 km to the west of the Indian Ocean. Aerosol samples were collected using a ''Gent'' PM10 stacked filter unit (SFU)

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sampler, PM10(NN), (Maenhaut et al., 1994; Hopke et al., 1997) with coarse (Apiezon-coated) and fine Nuclepore polycarbonate filters (pore sizes 8 and 0.4 µm, respectively). The sampler operated at a flow rate of 17 L/min. At this flow rate the coarse filter of the SFU sampler collects the particles with aerodynamic diameter (AD) between 2 and 10 µm, while the fine filter collects the size fraction < 2 µm AD. The samplers were placed on the roof of a building 6 m above ground level at the main campus of Sokoine University of Agriculture (SUA). A detailed description of the site is given elsewhere (Mkoma et al., 2009a). During the dry season campaign between July and August 2005, a total of 51 samplings and 7 field blanks (of 30 s) were performed. The first 5 samplings were of 24 hours and the subsequent 46 samplings were daytime and nighttime collections of 12 hours each. The 24-hour samplings started at 8.00 am local time (UTC + 3 hours) and the 12-hour collections started at 6.30 am and 6.30 pm for daytime and nighttime respectively. The 2006 wet season campaign was carried out from March to April 2006, with 29 collections of 24 hours and 7 field blanks with each sampler. The exchange of filters during the 2006 wet season campaign was done at 8.00 am (Local time, UTC + 3 hours). From each campaign, the exposed filters and field blanks were placed into polycarbonate Petrislide dishes and kept frozen at -20 ^{o}C during storage and transported cool to the Institute for Nuclear Sciences, INW (Ghent, Belgium) for analysis.

The PM mass of the collected field blanks and actual samples were obtained by weighing the filters before and after sampling with a Mettler MT5 microbalance (sensitivity 1 µg). Before weighing, the filters were conditioned at relative humidity of 50% and a temperature of 20 ^{o}C for 24 hour and the weighings were done at these conditions. The uncertainty (1 standard deviation) of the PM mass determinations is estimated at 5 µg for the Nuclepore polycarbonate filters (Hitzenberger et al., 2004). Furthermore, one half of each Nuclepore polycarbonate filter (coarse and fine) was placed in a 15 mL polystyrene tube and ultrasonically extracted with 10 mL of Millipore Simplicity water for 1 hour. The major water-soluble inorganic ions, namely Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, NO_3^- and Cl^- in the extracts were then analysed by ion chromatography (IC), using a Dionex 4500i instrument as described in detail elsewhere (Maenhaut et al. 2002). All the reported water-soluble ion concentrations and PM mass have been corrected using field blanks and the data for the coarse (PM10-2) and fine (PM2) filters were added in order to obtain a total PM10 data.

Results and discussions

i) PM mass concentration

The mean mass concentrations and associated standard deviation for the fine, coarse, PM10 size fractions during the 2005 dry season campaign were 17±4, 52±27, 69±29 µg/m^3 respectively. The corresponding values for the 2006 wet season campaign were 13±5, 34±23 and 47±25 respectively. The average contributions of fine (PM2) particulate mass to the PM10 mass during the two campaigns were 49 ± 9 and 37 ± 6 % for the 2005 dry, and 2006 wet seasons, respectively, indicating that most of the PM10 mass was in the coarse size fraction. The time series of the PM mass in the fine, coarse and PM10 size fractions obtained at our sampling site in Morogoro during the two seasons campaigns are shown in Figures 1 and 2. The concentrations of the PM mass in all size fractions showed seasonal differences, with the 2005 dry season campaign having the highest concentrations. The variations in ambient PM10 levels observed during the campaigns resulted from variations in sources strengths and in meteorological conditions, such as mixing height and precipitation. As for day and night samples of the 2005 dry season campaign, the site showed day/night differences for the PM10-2 and PM10 mass levels which are expected to be attributed by primary sources such as soil dust dispersion and intense biomass burning during the day.

Since there are no standard limits for PM10 or PM2.5 levels in Tanzania, the data from this work are compared to EU standards. In the EU the daily limit concentration for PM10 mass is 50 µg/m^3, which cannot be exceeded more than 35 times per year, and the yearly average concentration (based on daily measurements) is 40 µg/m^3 (EU Directive, 1999). In Morogoro, the daily PM10 concentrations exceeded the daily EU standard 17 times during the 2005 dry season campaign and was within the limit in 2006 wet season campaign.

The levels of the PM10 mass at the rural background site of Morogoro are in line with the levels at rural sites in Europe, as reported in the European aerosol phenomenology study (Van Dingenen et al., 2004). Our data where also comparable to the few available other data sets for eastern and southern Africa. For the remote site of Rukomechi in northern Zimbabwe, median PM10 mass concentrations of 8 µg/m^3 and 23 µg/m^3 were obtained for the wet and the dry seasons, respectively (Nyanganyura et al., 2007), which are lower than the data for Morogoro.

ii) Concentration of water-soluble ions

The chemical characteristics of the water-soluble inorganic ions in the coarse and fine size fractions collected during the 2005 dry season and 2006 wet season campaigns in Morogoro are shown in Table 1 (Note that the median data for the water-soluble ions during the 2005 dry season campaign have also reported in Mkoma et al., 2009b). In both size fractions, the mean concentration for the anions Cl^-, NO_3^-, and SO_4^{2-} and the cations Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, are highest in the 2005 dry season campaign and lowest in the 2006 wet season campaign. However, Ca^{2+} was the most important cation and the SO_4^{2-} main anionic species in PM10 while NH_4^+ was the most abundant cation in the fine size fraction and Cl^- the main anionic species in the coarse fraction.

The median SO_4^{2-} and NO_3^- concentration in the 2005 dry season campaign was 4.5 and 8.5 times respectively higher than in the 2006 wet season campaigns. The difference between seasons is more pronounced for nitrate than for sulphate. The partition of NO_3^- between the gas phase and particulate phase depends strongly on temperature (T), relative humidity (RH), and ammonia concentration, and larger particulate nitrate concentrations are expected at low temperature and high RH. There was no dramatic seasonal difference in RH, whereas the temperature was lowest in the dry season. Thus, the larger nitrate levels in this season are expected. On the other hand, biomass burning is an important source of NO_x, the precursor gas of nitrate, and enhanced biomass burning in the dry season may be responsible for the elevated nitrate levels then. The median for particulate NH_4^+ is also higher in the dry than in the wet season. This may be due to enhanced ammonia levels then. Unfortunately, no data for the gases SO_2, NO_x, and NH_3 are available for the 3 campaigns. The medians for Ca^{2+}, Na^+, Mg^{2+}, K^+, and Cl^- are higher in the dry than in the wet season campaigns. The highest median for K^+ in the dry season campaign is expected, as K^+ is a good indicator for biomass burning, which is most enhanced in the dry season. When compared to literature data for rural sites in Europe, it appears that the levels in PM10 of SO_4^{2-}, NO_3^-, and NH_4^+ are substantially lower at Morogoro than at the European rural sites (Putaud et al., 2004; Ocskay et al., 2006).

iii) Fine to PM10 ratios

The average fine to PM10 concentration ratios were calculated for the PM mass, and various water-soluble inorganic ions; the results are shown in Figure 3. The average PM2/PM10 concentration ratios and associated standard deviations for the PM mass were 0.49 ± 0.09, and 0.37 ± 0.06 for the 2005 dry, and 2006 wet season campaigns, respectively. The higher PM2/PM10 ratio for the PM mass in the dry season may be due to a larger contribution from pyrogenic aerosol, which is known to be mostly associated with fine particles. Figure 3 further shows that ammonium and sulphate were mainly present in the fine size fraction. In contrast, nitrate was mainly associated with the coarse particles especially during the 2006 wet season campaigns which accounted for 65% of the PM10 NO_3^-. The sea-salt elements (Na, Mg, Cl) were predominantly associated with the coarse size fraction. K (a well-known indicator for biomass burning) was mostly associated with the fine particles (in contrast to Ca). This suggests that biomass burning was important in Morogoro, especially in the 2005 dry season campaign, when around 80% of the PM10 K was in the PM2 size fraction.

iv) Ratios of cationic and anionic species in explaining PM source and relationship between NH_4^+, SO_4^{2-} and NO_3^-

Various equivalent concentration ratios were calculated for the water-soluble inorganic species, including the ion balance (expressed as the ratio of total cation equivalents to total anion equivalents), the ratios of individual cations to the total cations and of individual anions to the total anions, and the $C1^-/Na^+$ ratio. Figure 4 shows the relationship between the total cation equivalents against the total anion equivalents in PM10 data from the entire study period. The slope of the regression equation of the total cation data (in neq/m^3) on the total anion data (neq/m^3) is 1.35 and the r^2-value is 0.92. This indicates that the total equivalent cation concentration was somewhat larger than that of the anions.

The median ratios and ranges for the fine and coarse size fractions for each of the three campaigns are given in Table 2. The median ion balance ratios are all larger than 1.0; they range from 1.30 to 1.44 for the fine size fraction and from 2.01 to 3.14 for the coarse size fraction. It should be indicated that carbonates were not measured by IC; these missing carbonates are thought to be largely responsible for the observed deviation from 1.0. If we assume that all the Ca^{2+} is present as $CaCO_3$ and recalculate the ion balances with Ca^{2+} excluded, then the new median ion balance ratios range from 1.17 to 1.25 for the fine size fraction and from 1.02 to 1.22 for the coarse fraction. These new medians are all fairly close to 1.0. That Ca^{2+} may be present as $CaCO_3$ is not an unreasonable supposition, as limestone soils often contribute substantially to the mineral dust aerosol.

Table 2 further shows that SO_4^{2-} is by far the most prominent anion and that NH_4^+ is the main cation in the fine size fraction; in the coarse fraction, Cl^- and Ca^{2+} are the main anionic and cationic species. As just indicated, Ca^{2+} may be present as $CaCO_3$. With regard to Cl^-, this may be mainly be derived from sea salt. To examine this, the Cl/Na^+ equivalent ratios of Table 2 can be compared with the ratio of 1.18 for sea water (Brewer, 1975). The median $C1^-/Na^+$ ratios range from 0.18 to 0.26 for the fine size fraction and from 0.69 to 0.79 for the coarse size fraction. All these medians are substantially lower than the sea-water ratio. Not all Na^+ at the Morogoro site may originate from sea salt, though. There is also Na in mineral dust. Actually, the calculated crustal enrichment factor (EF) for coarse Na is near 1, so that the low $C1^-/Na^+$ coarse medians may well be due to the contribution from mineral dust Na. It should be noted here that at locations where there is virtually no contribution from sea salt, one often sees crustal EFs for Na of lower than 1 (sometimes even below 0.5), indicating that the EF of 1 does not imply that all the Na is fully derived from mineral dust. As to the fine size fraction, the mean crustal EFs for Na are about 2 in the two campaigns, suggesting that at least half of the fine Na may be coming from non-crustal sources, such as sea salt. Even taking this into account, we would never arrive at $C1^-/Na^+$ ratios that approach that in sea water. It is well-known, though that Cl may be lost from the fine sea-salt aerosol because of reactions with acidic gases and acidic aerosol species (e.g., Graedel and Keene, 1995) both in the atmosphere and during the actual sampling.

The medians and ranges of the molar ratios of ammonium to sulphate and nitrate are also given in Table 2. As indicated above, in the fine size fraction, SO_4^{2-} is by far the most prominent anion and NH_4^+ is the main cation. In the neutralization of the precursor gases H_2SO_4 and HNO_3 by NH_3 gas and the formation of particulate compounds, H_2SO_4 is neutralized [first to NH_4HSO_4, then to $(NH_4)_2SO_4$] before the neutralization of HNO_3 takes place. Only in the case of an ammonia-rich environment will the H_2SO_4 and HNO_3 be fully converted to the ammonium salts (Seinfeld and Pandis, 1998). It follows from the data in Table 2 that there was insufficient NH_4^+ to fully neutralize H_2SO_4 to $(NH_4)_2SO_4$, in the fine size fraction, during the 2005 dry season campaign, but that there was nearly sufficient NH_4^+ for this neutralization in the 2006 wet season campaign. H_2SO_4 and sulphate in the atmosphere are formed through homogeneous gas phase and heterogeneous gas/particle phase oxidation of SO_2. The atmospheric lifetime of fine sulphate is in the order of several days (Seinfeld and Pandis, 1998), so it can be transported far away from the sources of the SO_2. With regard to the sulphate in the coarse size fraction, this is to some extent primary (e.g., derived from sea salt) and in part secondary (formed from SO_2). Table 2 indicates that a substantial fraction of the coarse sulphate may have been present as NH_4HSO_4 and $(NH_4)_2SO_4$ during the 2006 wet season campaign, but that there was very little of these ammonium salts in the 2005 dry season campaign. The neutralizing cations for coarse sulphate in this latter campaign must therefore have been alkali and/or earth alkali metals (e.g., Ca^{2+}).

Fine particulate nitrate is formed by homogeneous gas phase oxidation of nitrogen oxides (NO_x) to gaseous nitric acid, which is followed by the reaction with gaseous ammonia to form highly volatile NH_4NO_3. The distribution of NH_4NO_3 between the gas phase and particle phases depends mainly upon meteorological conditions (temperature and relative humidity), on the aerosol composition, and on the acidity of the particles. As indicated above, the chemical reaction between sulphuric acid and ammonia is the preferred chemical reaction in the atmosphere (Baek et al., 2004). As there was insufficient NH_4^+ in the fine fraction to fully neutralize the fine sulphate, the formation of particulate NH_4NO_3 was inhibited and most of the NO_3^- may have been in the gas phase (as HNO_3). However, gaseous nitric acid may react with alkaline particles, which are mainly present in the coarse size fraction, such as sea salt and soil particles (Pakkanen, 1996) and thereby be converted into coarse nitrate. It is therefore not surprising that more than half of the PM10 nitrate was present in the coarse size fraction (see Figure 3, especially 2006 wet season campaign), whereas PM10 ammonium and sulphate were predominantly associated with the fine aerosol.

Influence of meteorology on the concentration of the PM mass and other aerosol components

a) Impact of meteorology on the PM mass

Many studies have indicated that the PM10 mass concentrations in the ambient air are affected by various meteorological factors such as temperature, wind speed, rainfall, and relative humidity (Rajkumar and Chang, 2000). The daily average meteorological parameters (wind speed, cumulative precipitation, temperature, and relative humidity) were obtained from the Tanzania Meteorological Agency (SUA-station). The daily average wind speed during the campaigns ranged from 0.0 to 3.6 m/s. The winds were predominantly blowing from the south-east for most of the sampling periods. The daily average temperature ranged from 14 °C to 31 °C. The daily mean relative humidity ranged from 50% to 90%, with the lower value typically recorded in the dry season. The cumulative precipitation varied from nearly zero during the 2005 dry season campaign to 248 mm during the 2006 wet season campaign. The correlations of the PM10 mass concentrations with different meteorological parameters were examined.

Relationship between PM10 mass and total daily cumulative precipitation is shown in Figure 5(a). The PM10 mass concentration was systematically low during precipitation events. It never exceeded 20 $\mu g/m^3$ when the daily precipitation was higher than 5 mm. The variation of PM10 mass concentration with daily mean temperature is shown in Figure 5(b). The concentrations were higher at low temperatures (below about 24 °C) and high temperature (above about 27 °C), and reached a minimum for temperatures between 24 and 27 °C. One could make a number of assumptions to explain this observation. The rise in concentration at low temperatures could be due to more frequent inversion events. The altitude of the site (526 m above sea level), as well as the morphology of the foothill of the Uluguru Mountain ranges, make that the site is rather sensitive to the phenomenon of temperature inversion. The higher PM10 mass concentrations at higher temperatures might be caused by more intense formation of secondary aerosols. The influence of the daily mean wind speed on PM10 mass (Figure 5(c)) is less clear than that of the meteorological parameters discussed above. Low wind speeds inhibit dilution whereas large wind speeds lead to increased soil dust mobilisation. It seems that the effects of decreased dilution and increased soil dust mobilisation were roughly of equal importance.

b) Impact of temperature and relative humidity on anion concentrations

The relationship between the atmospheric concentrations in PM10 of the anions and temperature and relative humidity was examined. To do this, the data were selected excluding rainy periods and classified according to ambient temperature and relative humidity levels. The sensitivity of particulate SO_4^{2-}, NO_3^-, and Cl^- concentrations to changes of temperature and relative humidity is shown in Figure 6. There was virtually no dependence on relative humidity, while temperature dependence could be found. The change in particulate SO_4^{2-}, NO_3^-, and Cl^- concentrations with temperature resembles the change for the PM10 mass: lower levels at temperatures between 23 and 27 °C.

Conclusion

The concentrations of the water-soluble ions were influenced by the meteorology; higher mean concentration for the anions Cl^-, NO_3^-, and SO_4^{2-} and the cations Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, were observed during the 2005 dry season campaign than during the 2006 wet season campaign. NH_4^+, K^+, and SO_4^{2-} were mainly present in the fine size fraction. The sea-salt elements (Na, Mg, Cl), Ca^{2+}, and NO_3^- were predominantly associated with the coarse size fraction. However, Ca^{2+} was the most important cation and the SO_4^{2-} main anionic species in PM10 while NH_4^+ was the most abundant cation in the fine size fraction and Cl^- the main anionic species in the coarse fraction. The study suggest that primary sources such as soil dust dispersion and biomass burning made a significant contribution to the ambient particulate pollution in Morogoro atmosphere.

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Table 1. The mean mass concentration and associated standard deviation (in neq/m^3) of water-soluble.

	2005 dry season				2006 wet season			
	Fine		Coarse		Fine		Coarse	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
NH_4^+	371.33	339.80	12.04	24.67	154.09	88.98	9.76	7.99
SO_4^{2-}	1881.69	1037.99	419.38	196.08	452.64	258.84	96.71	84.59
NO_3^-	774.79	480.70	823.07	416.44	63.82	27.30	167.22	172.35
Cl^-	168.74	123.96	909.69	364.88	10.76	8.38	138.98	165.82
Na^+	306.98	110.82	750.54	254.10	36.30	23.11	120.67	131.09
Mg^{2+}	20.79	8.98	140.40	38.49	5.46	3.42	28.05	15.94
K^+	1221.27	557.80	146.79	46.30	71.95	26.94	55.33	12.80
Ca^{2+}	117.31	44.19	961.86	346.71	35.39	21.35	313.98	194.49

Table 2. Medians (and ranges) of concentrations in the fine and coarse size fractions at Morogoro.

Species	Fine size fraction		Coarse size fraction	
	Median	Range	Median	Range
2005 dry				
cations/anions	1.30	(1.12 – 1.64)	2.01	(1.21 – 5.45)
NH_4^+/cations	0.22	(0.07 – 0.71)	0.002	(0.00 – 0.06)
Na^+/cations	0.21	(0.07 – 0.36)	0.36	(0.09 – 0.55)
Mg^{2+}/cations	0.02	(0.005 – 0.067)	0.12	(0.07 – 0.16)
K^+/cations	0.45	0.17 – 0.62)	0.04	(0.02 – 0.08)
Ca^{2+}/cations	0.08	(0.02 – 0.23)	0.48	(0.24 – 0.81)
NO_3^-/anions	0.23	(0.05 – 0.43)	0.27	(0.01 – 0.44)
SO_4^{2-}/anions	0.69	(0.39 – 0.93)	0.16	(0.11 – 0.32)
Cl^-/anions	0.08	(0.01 – 0.26)	0.54	(0.24 – 0.82)
Cl^-/Na^+	0.26	(0.07 – 1.21)	0.79	(0.39 – 1.09)
NH_4^+/SO_4^{2-}	0.92	0.45 – 1.97	0.09	0.0 – 1.71
$NH_4^+/(2SO_4^{2-})$	0.46	0.22 – 0.99	0.04	0.0 – 0.17
$NH_4^+/(2SO_4^{2-} + NO_3^-)$	0.34	0.12 – 0.93	0.01	0.0 – 0.21
2006 wet				
cations/anions	1.34	(1.05 – 1.59)	3.14	(1.28 – 8.09)
NH_4^+/cations	0.59	(0.37 – 0.79)	0.02	(0.01 – 0.12)
Na^+/cations	0.11	(0.03 – 0.19)	0.17	(0.02 – 0.48)
Mg^{2+}/cations	0.03	(0.01 – 0.05)	0.09	(0.06 – 0.13)
K^+/cations	0.13	(0.06 – 0.36)	0.06	(0.02 – 0.16)
Ca^{2+}/cations	0.12	(0.04 – 0.32)	0.63	(0.38 – 0.82)
NO_3^-/anions	0.09	(0.06 – 0.21)	0.29	(0.14 – 0.40)
SO_4^{2-}/anions	0.86	(0.69 – 0.94)	0.22	(0.09 – 0.58)
Cl^-/anions	0.03	(0.00 – 0.09)	0.43	(0.12 – 0.56)
Cl^-/Na^+	0.19	(0.00 – 0.79)	0.70	(0.45 – 2.91)
NH_4^+/SO_4^{2-}	1.84	1.37 – 2.58	0.79	0.31 – 4.32
$NH_4^+/(2SO_4^{2-})$	0.91	0.68 – 1.29	0.40	0.16 – 2.16
$NH_4^+/(2SO_4^{2-} + NO_3^-)$	0.84	0.61 – 1.08	0.14	0.04 – 0.88

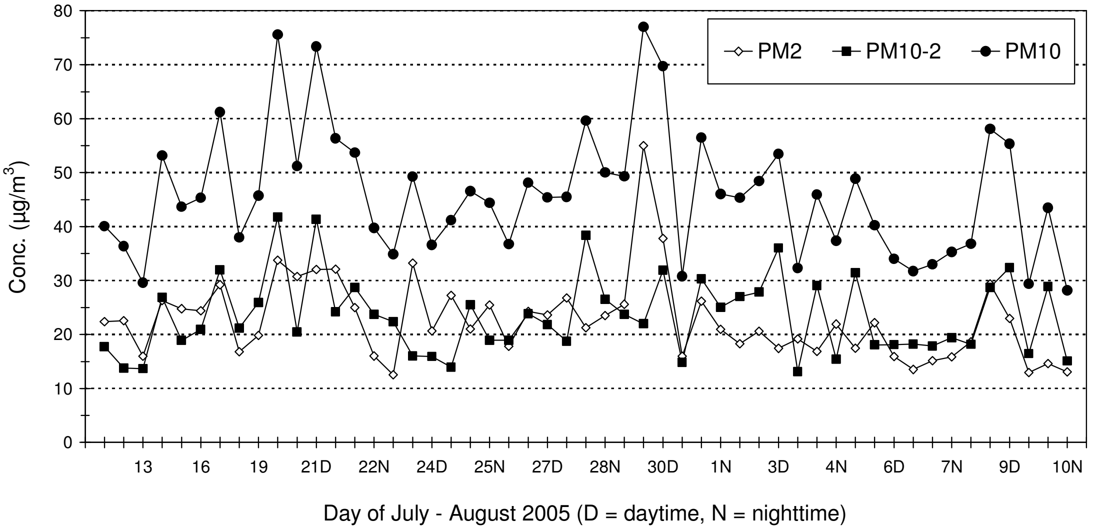

Figure 1. Time series of the PM mass in the fine, coarse and PM10 size fractions at Morogoro during the 2005 dry season campaign.

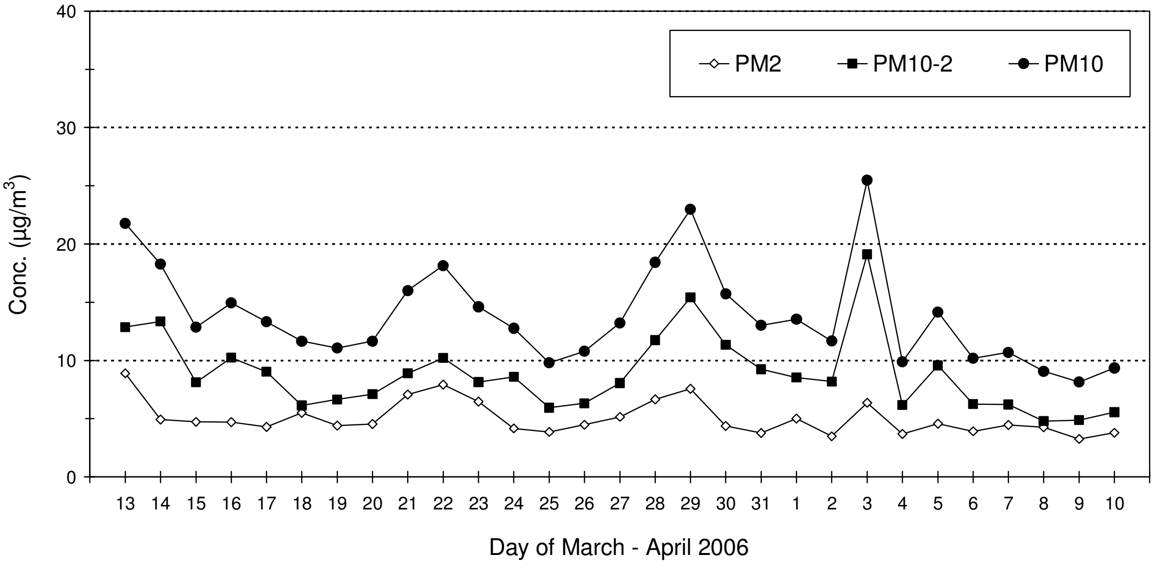

Figure 2. Time series of the PM mass in the fine, coarse and PM10 size fractions at Morogoro during the 2006 wet season campaign.

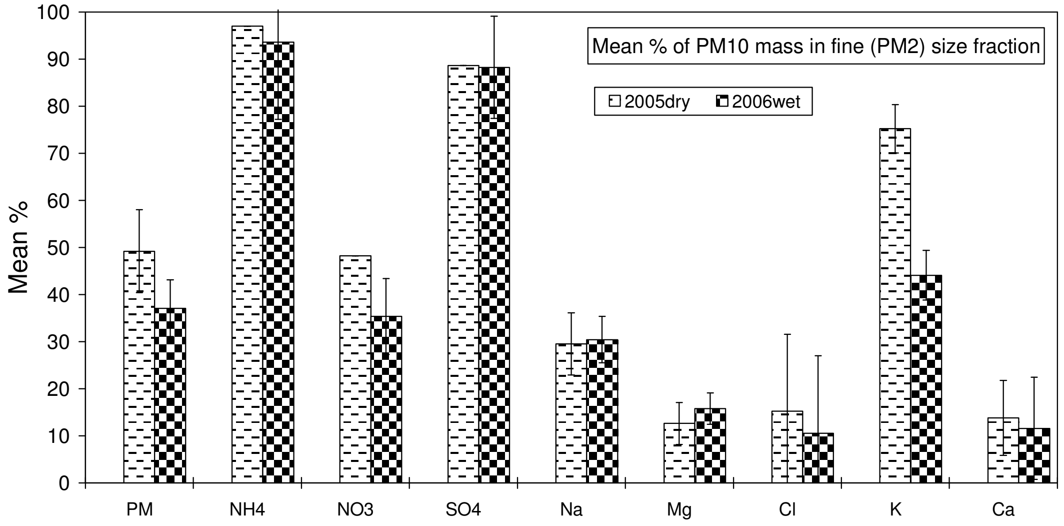

Figure 3. Mean percentage and associated standard deviation of the PM10 aerosol in the fine (PM2) size fraction for the PM mass and the water soluble inorganic ions during 2005 dry season and 2006 wet season campaigns in Morogoro.

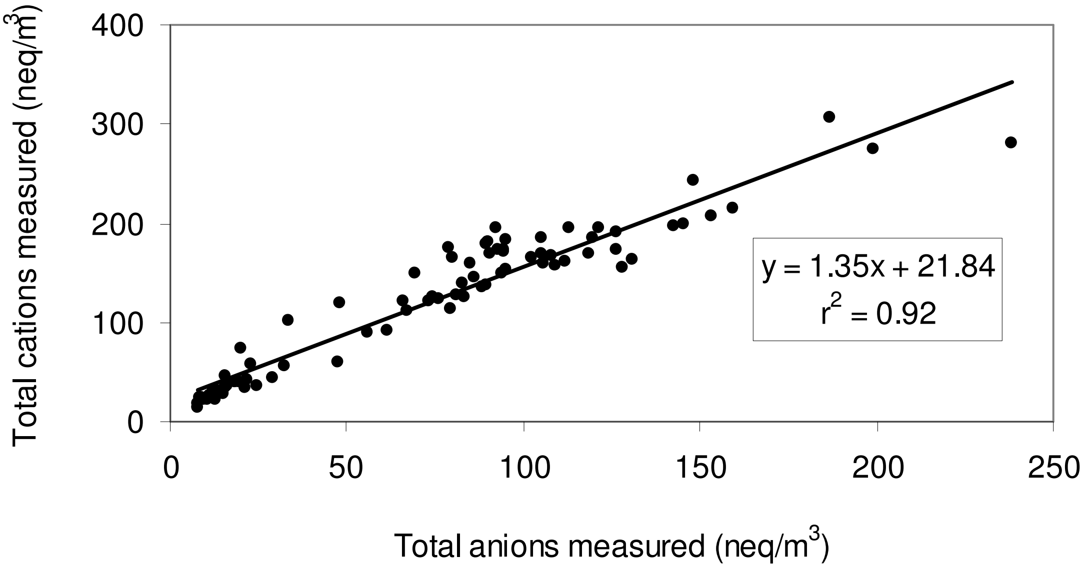

Figure 4. The correlation between total cations and anions measured in PM10 (N = 80) for Morogoro during the study period.

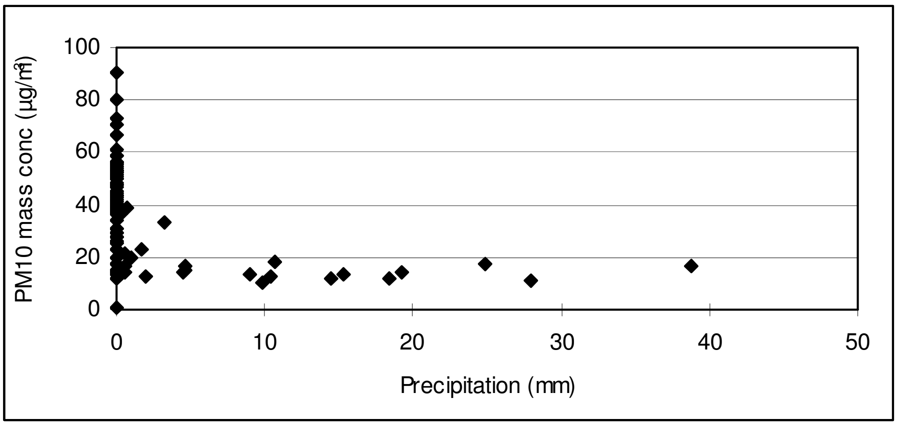

Figure 5a. Relationship between PM10 mass and total daily cumulative precipitation,

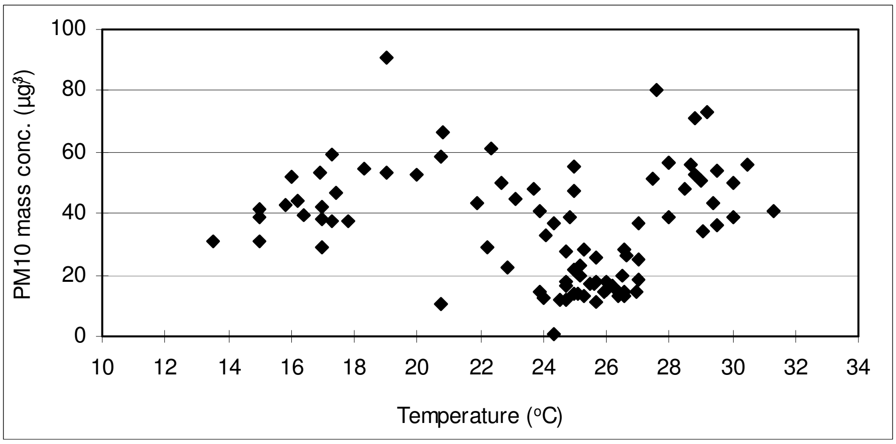

Figure 5b. Relationship between PM10 mass and daily mean temperature

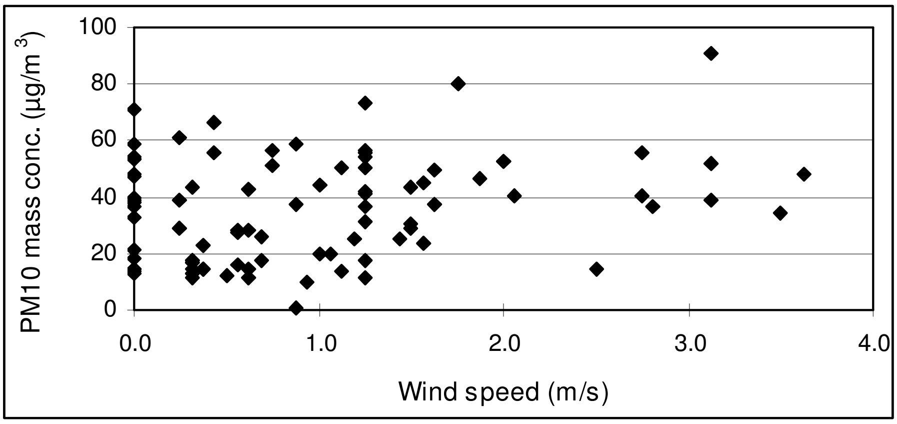

Figure 5c. Relationship between PM10 mass and daily mean wind speed.

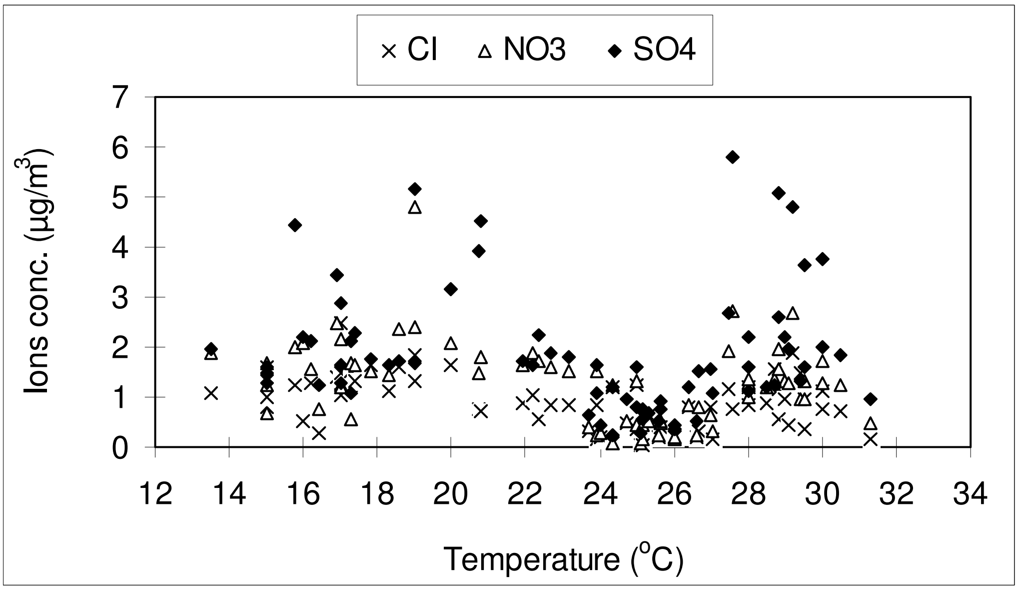

Figure 6a. Relationship between the atmospheric concentration of the anions and temperature

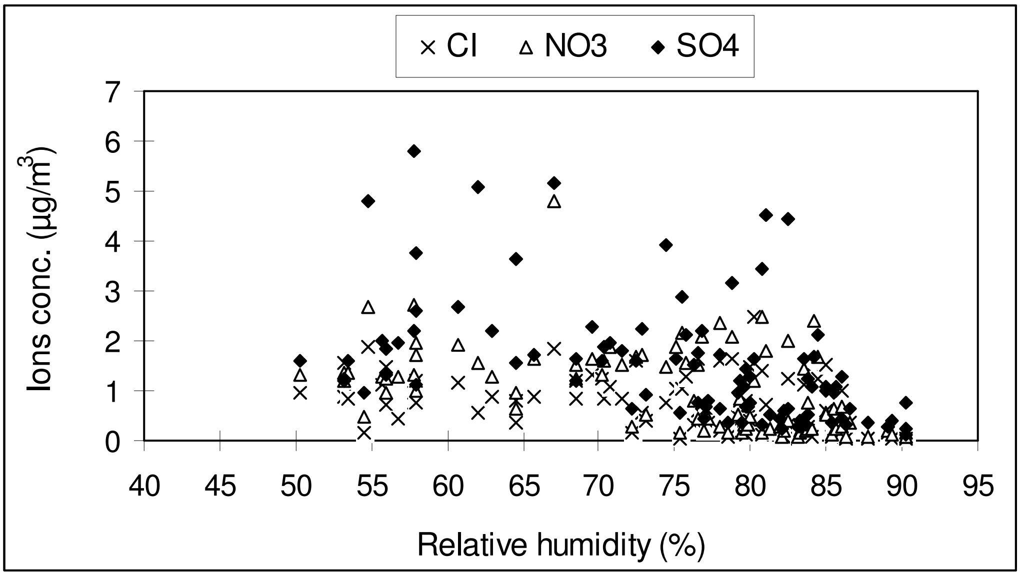

Figure 6b. Relationship between the atmospheric concentration of the anions and relative humidity.