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**Implication for
biomass burning
contribution to
organic aerosols**

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Carbonaceous components, levoglucosan and inorganic ions in tropical aerosols from Tanzania, East Africa: implication for biomass burning contribution to organic aerosols

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Atmospheric aerosol samples of $PM_{2.5}$ and PM_{10} were collected at a rural site in Tanzania in 2011 during wet and dry seasons and they were analysed for carbonaceous components, levoglucosan and water-soluble inorganic ions. The mean mass concentrations of $PM_{2.5}$ and PM_{10} were $28.2 \pm 6.4 \mu\text{g m}^{-3}$ and $47 \pm 8.2 \mu\text{g m}^{-3}$ in wet season, and $39.1 \pm 9.8 \mu\text{g m}^{-3}$ and $61.4 \pm 19.2 \mu\text{g m}^{-3}$ in dry season, respectively. Total carbon (TC) accounted for 16–19% of the $PM_{2.5}$ mass and 13–15% of the PM_{10} mass. On average, 85.9 to 88.7% of TC in $PM_{2.5}$ and 87.2 to 90.1% in PM_{10} was organic carbon (OC), of which 67–72% and 63% was found to be water-soluble organic carbon (WSOC) in $PM_{2.5}$ and PM_{10} , respectively. Water-soluble potassium (K^+) and sulphate (SO_4^{2-}) in $PM_{2.5}$ and, sodium (Na^+) and SO_4^{2-} in PM_{10} were the dominant ionic species. We found, that concentrations of biomass burning tracers (levoglucosan and mannosan) well correlated with non-sea-salt- K^+ , WSOC and OC in the aerosols from Tanzania, East Africa. Mean contributions of levoglucosan to OC ranged between 3.9–4.2% for $PM_{2.5}$ and 3.5–3.8% for PM_{10} . This study demonstrates that emissions from biomass- and biofuel-burning activities followed by atmospheric photochemical processes mainly control the air quality in Tanzania.

1 Introduction

Africa is facing air pollution problems with particulate matter (PM) due to its growing economy. Atmospheric aerosols that are derived from both natural and anthropogenic sources have been reported around the world (Medeiros et al., 2006; Nyanganyura et al., 2007; Harrison and Yin, 2008; Engling et al., 2011; Pavuluri et al., 2011). Biomass burning which is associated with domestic and open fires has drawn global concern for its effects on human health, visibility and global climate. In areas with intensive land use changes or agricultural practices, field burning of biomass and agricultural wastes is an important source of aerosol particles and trace gases in the atmosphere (Andreae

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and Merlet, 2001; Koe et al., 2001; Streets et al., 2003). The major types of biomass burning in Africa include forest and savanna fires (Cachier et al., 1991, 1995; Lacaux et al., 1993; Liu et al., 2000). However, in Tanzania agricultural field burning and forest fires are the dominant biomass burning types, which may be the most important source of atmospheric aerosols during the dry season.

Carbonaceous materials and water-soluble ions are the major components of atmospheric aerosols. Carbonaceous aerosols, which consist of elemental carbon and a complex mixture of numerous organic compounds, can account for 20 to 50 % of $PM_{2.5}$ mass in urban and rural locations (Querol et al., 2009) whereas water-soluble ions can comprise up to 60–70 % of particulate mass (Xiu et al., 2004). On the other hand, a large portion of water-soluble organic species (e.g. water-soluble organic compounds) are related to the formation of secondary organic aerosols (Miyazaki et al., 2006) and also have been well recognized to be emitted from biofuel and/or biomass burning (Mayol-Bracero et al., 2002). Levoglucosan (LG) (1,6-Anhydro- β -D-glucopyranose), water-soluble potassium and even organic carbon are known to be the typical components of biomass burning aerosol (Cachier et al., 1995; Simoneit et al., 1999). Potassium has been used as a conventional biomass-burning tracer (Cachier et al., 1991), whereas levoglucosan, which is produced by the pyrolysis of cellulose and hemicellulose, has been used as a unique molecular tracer of biomass burning aerosols (Simoneit et al., 1999; Fraser and Lakshmanan, 2000). Because levoglucosan is specific to cellulose and hemicellulose burning, it has more advantage than water-soluble potassium in assessing the contribution of biomass burning to ambient aerosols (Puxbaum et al., 2007; Zhang et al., 2008). In addition, the ratio of levoglucosan to mannosan has been proposed as an indicator for different biomass fuel types (Schmidl et al., 2008; Engling et al., 2009).

Tanzania as a whole does not suffer serious air pollution problems yet but localized pollution does occur due to its growing population, agricultural and industrial activities. Unfortunately, compared with the chemical characterisation performed for atmospheric aerosols in other countries around the world, such studies in Africa and in particular

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Tanzania have not been conducted for organic aerosols (Cachier et al., 1991; Maenhaut et al., 1996; Gao et al., 2003). In addition, biomass-burning activities in Tanzania are common phenomena, however, the studies of atmospheric aerosols have not been reported in East Africa in particular in relation to specific tracers such as levoglucosan (Simoneit et al., 1999). Therefore, a better understanding of aerosol characterization and source identification on a local and regional scale is needed. The objective of this study is to investigate the seasonal variations in the chemical characteristics of carbonaceous components, levoglucosan and major water-soluble inorganic ions in $PM_{2.5}$ and PM_{10} . Here, we discuss the contribution of biomass burning to the ambient aerosols at a rural background site in Morogoro, Tanzania.

2 Experimental

2.1 Sampling site and aerosol collection

Intensive aerosol sampling campaigns were carried out at a rural background site in Morogoro ($6^{\circ}47'40.8''$ S, $37^{\circ}37'44.5''$ E, altitude 504 m a.s.l.) during the wet season (30 May to 13 June 2011) and the dry season (28 July to 8 August 2011). This site is located at about 200 km west of the Indian Ocean and the city of Dar es Salaam, a business capital in Tanzania. The possible main local aerosol sources include domestic fires, field burning of crop residue and waste, emissions from livestock (cattle dairy or farm) and forest fires. Aerosol collections were made at 2.7 m above ground level using $PM_{2.5}$ and PM_{10} low volume samplers (Gent type, flow rate 17 l min^{-1}) in parallel (Maenhaut et al., 1994; Hopke et al., 1997). The two samplers were equipped with quartz fibre filters (Pallflex 2500QAT-UP, 47 mm) which were pre-baked at 450°C for 4 h in a furnace to eliminate adsorbed organics before use. The samplers were setup at a meteorological synoptic station located within the Solomon Mahlangu Campus of Sokoine University of Agriculture (SUA). The site and its large radius were covered by

grass (vegetation), hence it is not possible for immediate local soil dust to interfere with the sampling.

The sample collection was conducted in approximately 24 h intervals and the exchange of filters was done at 07:30 a.m. The meteorological data, including precipitation, ambient temperature and relative humidity for the sampling days, are described in Sect. 2.3. A total of 21 sets of samples and 2 field blanks (samplings of 30 s) were collected for each sampler and used in this study. Before and after sampling the filters were placed in a pre-heated glass jar with a Teflon-lined screw cap and kept frozen at -20°C during storage and transported to the atmospheric chemistry laboratory at the Institute of Low Temperature Sciences (ILTS), Hokkaido University (Japan). The samples were stored in a freezer at -20°C prior to analysis. All the procedures were strictly quality-controlled to avoid any possible contamination of the samples.

2.2 Chemical analyses

2.2.1 PM mass measurement

For the determination of particulate mass, filters were weighed before and after sampling with a high sensitivity analytical microbalance (Sartorius Model M2P, detection limit $1\ \mu\text{g}$). Before weighing, the filters were conditioned to room temperature (20°C) and a relative humidity of 50 %.

2.2.2 Carbonaceous aerosols components

The concentrations of organic carbon (OC) and elemental carbon (EC) were determined using thermal-optical transmission method (Sunset Laboratory Inc., USA) (Birch and Cary, 1996) following the Interagency Monitoring Protected Visual Environments (IMPROVE) thermal evolution protocol. A $1.54\ \text{cm}^2$ portion of each quartz fibre filter was placed in a quartz tube inside the thermal desorption chamber of the analyzer and heated stepwise as described in detail by Wang et al. (2005). Briefly, helium (He) gas

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is applied in the first ramp and is switched to helium/oxygen (He/O_2) mixture in the second ramp. The evolved carbon dioxide (CO_2) at each temperature step was measured by a Non-Dispersive Infrared detector system and the transmittance of light (red 660 nm) through the filter punch was used for determining the OC/EC split. It should be noted that in this study a tandem filter set-up was used to account for positive artefact particulate OC data (Viana et al., 2006). It is known that both positive (i.e. adsorption of volatile organic carbon that is assumed to prevail) and negative artefacts may occur for particulate OC when collecting aerosol samples with quartz fibre filters (Mader et al., 2003).

Water-soluble organic carbon (WSOC) was determined from a punch of 2.59 cm^2 from each quartz fibre filter. Each punch was placed in a 50 ml glass jar and extracted with 15 ml Milli-Q water under ultrasonication for 15 min. The extracts were then filtrated using a syringe filter (Millex-GV, $0.22 \mu\text{m}$) and analysed for WSOC using a Total Organic Carbon (TOC) analyzer (Model TOC-Vcsh, Shimadzu, Kyoto, Japan) (Miyazaki et al., 2011). The filter extract was acidified with 1.2 M HCl (hydrochloric acid) and purged with pure air in order to remove dissolved inorganic carbon and volatile organics before the measurement of WSOC. The reproducibility for triplicate analyses of laboratory standards was within 5 %.

All carbonaceous components in the reported data for the front filters have been corrected using the blank filters. The mean back to front filter ratio for OC was less than 10 % of that on the front filter during the campaigns. EC was not detected on the back filter whereas WSOC was negligible. The detection limits calculated as three times the standard deviation (3σ) of the OC and TC field blanks were $0.12\text{--}0.45 \mu\text{g C m}^{-3}$ for OC and TC, and $0.02\text{--}0.14 \mu\text{g C m}^{-3}$ for WSOC.

2.2.3 Levoglucosan

For the determination of levoglucosan, a biomass burning tracer, the detailed analytical procedures have been described in Fu et al. (2011). Briefly, a portion of each filters (1.54 cm^2) was extracted with dichloromethane/methanol (2 : 1; v/v) under

ultrasonication. The extracts were concentrated using a rotary evaporator under vacuum and then derivatized with 50 μl of N,O-bis-(trimethylsilyl)trifluoroacetamide (BSTFA) containing 1 % trimethylsilyl chloride and 10 μl of pyridine at 70 $^{\circ}\text{C}$ for 3 h. The derivatives were diluted by addition of 140 μl of *n*-hexane containing 1.43 $\text{ng}\mu\text{l}^{-1}$ of the internal standard (C_{13} *n*-alkane) and then determined with a gas chromatograph-mass spectrometer (GC/MS). The detection limit of levoglucosan was 0.06 ngm^{-3} .

2.2.4 Water-soluble inorganic ions

An ion chromatograph (761 Compact IC, Metrohm, Switzerland) was used for the analysis of the major water-soluble anions (sulphate SO_4^{2-} , nitrate NO_3^- , chloride Cl^- and methanesulphonate CH_3SO_3^- MSA^-) and cations (ammonium NH_4^+ , sodium Na^+ , potassium K^+ , magnesium Mg^{2+} and calcium Ca^{2+}). A 2.59 cm^2 punch of each quartz fibre filter was extracted twice with 5 ml ultrapure water (resistivity of > 18.2 $\text{M}\Omega\text{cm}$, Sartorius arium 611 UV) under ultrasonication for 15 min. The extracts were filtered through a syringe filter (Millex-GV, 0.22 μm pore size, Millipore) and injected in the IC for the analysis of inorganic ions. Anions were measured using a SI-90 4E Shodex column (Showa Denko, Tokyo, Japan) and an eluent of 1.8 mM Na_2CO_3 (sodium carbonate) plus 1.7 mM NaHCO_3 (sodium hydrogen carbonate) For cation analysis, we used a Metrosep C2-150 (Metrohm) column with 4 mM tartaric acid + 1 mM dipicolinic acid as the eluent. The injection loop volume was 200 μl for both cation and anion measurements. All ions were quantified against a standard calibration curve and the analytical errors in duplicate analysis of the authentic standards were within 7%. Limit of detection ranged from 0.006 to 0.02 ngl^{-1} for anions and 0.01 to 0.02 ngl^{-1} for cations. The reported concentrations for the PM mass, carbonaceous and ionic species are all corrected for field blanks. The non-sea-salt (nss)- SO_4^{2-} and nss- K^+ were calculated using Na^+ as a reference tracer for sea-salt.

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2.3 Meteorology

The climate of Tanzania is characterized by a warm, humid wet season (March–May) and a dry and somewhat cool dry season (July–September). The two seasons are distinguished by the passage of the inter-tropical convergence zone, with the northeasterly (NE) East African monsoon between November and March, and the southeasterly (SE) East African monsoon between April and October (Trewartha, 1961; Bargman, 1970). Morogoro, where the sampling site was located, experiences a humid tropical savanna climate with an annual average rainfall of 870 mm (ranges: 610–1180 mm) (TMA, 2011). During the two week wet season campaign, there were only 4 days without rain, however, few aerosol samples were met with a very weak rain. In contrast, there were 2 rainy days out of 14 during the dry season. The ambient temperature varied from 22.9 °C to 29.1 °C (average 26 °C) in wet season campaign and from 21.1 °C to 28.2 °C (average 24.6 °C) in dry season campaign. The daily average relative humidity ranged from 65 % to 96 % in the morning hours and from 41 % to 60 % in the afternoon. During the entire sampling period (May through August), the equatorial belt on the western coast of the Indian Ocean experienced mainly one type of wind pattern, that is, southeasterly monsoons.

2.4 Air mass trajectories

In order to identify the source regions of long-range transported air masses that arrived at Morogoro, 5-day air mass backward trajectories were computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) model from NOAA/ARL (<http://ready.arl.noaa.gov/HYSPLIT.php>; Draxler and Rolph, 2012). The isentropic backward trajectories were computed for arrival level of 500 m above ground level every 24 h at 12:00 UTC between the initial placement and the final collection of each filter. The observed trajectories that arrived in Morogoro show two major clusters that were dominant and similar during the wet and dry seasons. The backward

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air mass trajectory analysis showed that most air masses came from the oceanic over Madagascar, Mozambique or Tanzania (Fig. 1).

3 Results and discussion

3.1 PM mass concentration

5 Table 1 presents mass concentrations of PM_{2.5} and PM₁₀ aerosols collected during the 2011 campaigns in the wet and dry seasons at the rural site in Morogoro. The mean concentrations and associated standard deviation of the PM_{2.5} mass were 28.2 ± 6.4 µg m⁻³ in wet season and 39.1 ± 9.8 µg m⁻³ in dry season. The corresponding concentrations of the PM₁₀ mass were 47.0 ± 8.2 µg m⁻³ in wet season and
10 61.4 ± 19.2 µg m⁻³ in dry season. The mean concentrations of PM_{2.5} mass and PM₁₀ mass were higher in the dry than the wet season. The seasonal variations of the aerosol levels could be attributed to changes in source strengths and seasonal meteorology such as precipitation and mixing height. However, it should be noted that there were small differences in meteorological conditions especially on the temperature during the sampling days. In wet season, wet scavenging by rainfall could be efficient in removing the PM. During the dry season, unfavorable meteorological conditions (e.g. no rain and frequent inversion) and the enhanced emission from biomass burning could attribute to the enhanced higher concentration of PM. Basically, the main sources of the PM mass at this rural site are expected to be soil dust suspension and biomass
15 burning (i.e. primary sources), but gas-to-particle conversion processes may also be important.

In the previous studies conducted in 2005 during the wet and dry seasons and 2006 during the wet season at the Main campus of Sokoine University of Agriculture in Morogoro (about 10 km from the current sampling site), mean PM₁₀ mass concentrations
25 were obtained to be 28.4 ± 12.7 µg m⁻³, 48.7 ± 12.3 µg m⁻³ and 12.5 ± 12.7 µg m⁻³, respectively (Mkoma et al., 2009a,b, 2010a). These values for all campaigns and seasons

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are lower than the PM₁₀ mass concentrations measured in the current study (Table 1). Compared to the ambient air quality standards set by the Tanzania Bureau of Standards (TBS) for PM₁₀ (60 to 90 µg m⁻³), none of the PM₁₀ samples exceeded the TBS limit during the sampling periods (TBS, 2006). Currently, there is no ambient PM_{2.5} standard in Tanzania. The European Union (EU) daily limit concentration for PM₁₀ mass is 50 µg m⁻³, which cannot be exceeded more than 35 days per year, and the EU yearly average limit concentration is 40 µg m⁻³ (EU Directive 1999/30/EC, 1999). Nearly two thirds of our PM₁₀ mass data were higher than the EU daily limit and the average concentration for the entire sampling period is larger than the EU yearly limit. Nevertheless, the PM mass data from this rural site in Tanzania are comparable to the few available data sets from rural southern Africa (Nyanganyura et al., 2007). Our concentrations of PM₁₀ (Table 1) are also comparable to or lower than those reported from other sites in Europe and Asia (Van Dingenen et al., 2004; Gu et al., 2010; Maenhaut et al., 2011; Ram and Sarin, 2011).

3.2 Carbonaceous components

As seen from Table 1, the higher mean concentrations for TC, OC and EC were obtained in the dry season and the lower mean concentrations in the wet season. This trend in seasonality is consistent with that of the PM mass, which can be explained by the variations in source strengths and in part meteorological conditions. The mean concentrations of OC and EC in the PM_{2.5} fraction were 3.9 ± 1.3 and 0.5 ± 0.3 µg C m⁻³ for wet season and 6.0 ± 1.7 and 1.0 ± 0.3 µg C m⁻³ in dry season, respectively. The OC and EC concentrations in PM₁₀ were 5.6 ± 1.4 (7.9 ± 3.1) µg C m⁻³ and 0.7 ± 0.4 (1.3 ± 1.0) µg C m⁻³ for wet (dry) season, respectively. Concentrations of TC in the wet and dry seasons were 4.4 ± 1.4 µg C m⁻³ and 7 ± 1.9 µg C m⁻³ in PM_{2.5} aerosol and 6.3 ± 1.8 µg C m⁻³ and 9.3 ± 4.1 µg C m⁻³ in PM₁₀, respectively. These values are similar to those reported in our previous measurements (Mkoma et al., 2010b and references therein). Also our results are comparable with the few available other sets from rural

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sites in East Africa. For the rural site of Meru in Kenya, Gatari et al. (2003) reported a mean PM_{10} TC level of $7 \pm 1 \mu g C m^{-3}$. This mean value is similar to the mean TC data in PM_{10} obtained during the 2011 wet and dry season campaigns at our rural site in Tanzania.

Figure 2 shows the temporal variation of OC and EC concentrations and OC/EC ratio for $PM_{2.5}$ and PM_{10} aerosols. The OC and EC concentrations exhibited similar trends with small fluctuations in both size fractions during the sampling period. OC/EC ratios ranged from 2.3 to 17.2 (average 10.5) in $PM_{2.5}$ and from 4.9 to 17.8 (average 10.3) in PM_{10} during the wet season. Those of the dry season ranged from 2.9 to 10.7 (average 6.7) and 3.3 to 17.4 (average 8.1) for $PM_{2.5}$ and PM_{10} , respectively. Relatively high values of OC were observed in 29 July through 2 August 2011 possibly due to enhanced source strength. Low OC/EC ratios observed in this study might have been affected by the decrease in photochemical reactions, precipitation, and change in the particle size distribution. The somewhat high EC concentrations in dry season are likely due to the contributions from charcoal making process and domestic use as well as burning of agricultural wastes.

The relationship between OC and EC and the mass ratio of OC to EC have been used to identify origins, emission and transformation characteristics of carbonaceous aerosols (Turpin et al., 1991). As shown in Fig. 3, the correlation coefficients (r^2) of OC and EC were higher in dry season than those in wet season, indicating that during the dry season the OC and EC in $PM_{2.5}$ (Fig. 3a) had a co-genetic source. In PM_{10} , the correlation coefficients of OC and EC were somewhat comparable between the two seasons, suggesting that similar emission and transport processes affect OC and EC in this fraction (Fig. 3b). Biomass-burning emissions from wood fuel, agricultural waste and forest fires, and enhanced biogenic volatile organic compounds released from vegetation are the possible source of the carbonaceous components.

WSOC is a major water-soluble fraction in atmospheric aerosols that contribute to the number density of cloud condensation nuclei. The mean concentrations of WSOC in $PM_{2.5}$ and PM_{10} aerosols were 3 ± 1 and $3.5 \pm 0.6 \mu g C m^{-3}$ in wet season and 3.9 ± 0.9

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and $4.8 \pm 1.4 \mu\text{gC m}^{-3}$ in dry season, respectively (Table 1). The WSOC in our site may possibly originate from biogenic aerosols and/or wood burning (Andreae and Merlet, 2001; Maenhaut et al., 2007). Comparable WSOC/OC ratios were found between wet and dry seasons for $\text{PM}_{2.5}$ and PM_{10} . Time series of WSOC and WSOC/OC (Fig. 4) do not show any clear seasonal trend but show noticeable elevated WSOC levels at times during the sampling period. Compared with the previous studies at Morogoro (Mkoma et al., 2010b and references therein), the current study showed higher WSOC/OC ratios. The WSOC/OC ratios are reported to increase by the aging of organic aerosols (Aggarwal and Kawamura, 2009).

3.3 Levoglucosan and mannosan

Concentrations of levoglucosan during the campaigns ranged from 38 to 408 ng m^{-3} in $\text{PM}_{2.5}$ and from 49.5 to 658.7 ng m^{-3} in PM_{10} (Table 1). Mannosan, an isomer of levoglucosan, was also detected. Time series concentrations of levoglucosan in $\text{PM}_{2.5}$ and PM_{10} aerosols are shown in Fig. 5. The highest concentrations of levoglucosan in $\text{PM}_{2.5}$ were observed from 29 July to 3 August 2011 whereas in PM_{10} higher values are from 1–3 August 2011. During the wet and dry seasons levoglucosan accounted for on average, 4.7 % and 6.4 % of WSOC and 3.9 % and 4.2 % of OC in $\text{PM}_{2.5}$, respectively, whereas it accounted for 5.8 % and 6.3 % of WSOC and 3.5 % and 3.8 % of the OC in PM_{10} , respectively. Levoglucosan has been used as a specific biomass-burning marker (Simoneit et al., 1999; Puxbaum et al., 2007) and has been detected in various environments (Wang et al., 2006; Aggarwal and Kawamura, 2009; Fu et al., 2009; Stone et al., 2010; Zhang et al., 2012). Our results suggest that the studied aerosols are derived from biomass burning activities which are thought to be different between the two seasons. The emissions from open burning of agricultural waste and bush/vegetation fires in the dry season and domestic burning of wood, charcoal and waste might be the dominant sources of biomass burning-derived aerosols.

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3.4 Concentrations of major inorganic ions

Concentrations of inorganic water-soluble ions in $PM_{2.5}$ and PM_{10} were comparable between the two seasons although maximum concentrations were observed in dry season. Their temporal variations are shown in Fig. 6. It is noteworthy that daily variability of the ion in $PM_{2.5}$ and PM_{10} exhibited similar patterns with higher levels during 1–3 August. The ion distributions during the episode (1–3 August) are more pronounced with NH_4^+ and K^+ in $PM_{2.5}$, in which the abundance of NH_4^+ was comparable to that of SO_4^{2-} (Fig. 6). In $PM_{2.5}$, K^+ was the most abundant cation whereas SO_4^{2-} was the dominant anion. These ions accounted for 29.2 % and 9.3 % of the total ion mass, respectively. In PM_{10} , Na^+ and Ca^{2+} , the most abundant cations, accounted for 52.7 % of the total ions whereas SO_4^{2-} the dominant anion, accounted for 7.4 % of the total ions. The relative abundances of other inorganic ions such as NH_4^+ , Mg^{2+} , NO_3^- and Cl^- showed large variation but that of MSA was rather small ($< 1\%$). Although there were no significant seasonal differences in concentrations of most ions measured, the mean NO_3^- concentrations in dry season were 2 times higher than in wet season. The partitioning of NO_3^- between the gas phase and particles strongly depends on temperature, relative humidity, and ammonia concentration. Therefore, low temperature and enhanced biomass burning activities (an important source of NO_x) may be responsible for the difference in NO_3^- levels between the two seasons. There was a small seasonal difference in relative humidity during the sampling period.

The NH_4^+ concentrations in both seasons at our sampling site may be due elevated by the enhanced gaseous ammonia levels from biomass burning especially during smoldering combustion (Andreae and Merlet, 2001) or forest fires and from agricultural activities in particular cattle raising (Street et al., 2003; Stone et al., 2010). In addition, high NH_4^+ concentration could be caused by possible adsorption of NH_3 onto $PM_{2.5}$ particles due to enhanced levels of ammonia especially in the dry season (Tsaia and Pernga, 1998; Pathak and Chan, 2005). Unfortunately, no data for NH_3 gas are available for the campaigns. The highest mean concentration of K^+ was obtained in

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dry season. Because K^+ is a good indicator for biomass burning, this study indicates that biomass-burning events occurred often in dry season. The observed levels of the water-soluble ions are similar to those reported in the previous studies in Morogoro (Mkoma et al., 2009a; Mkoma et al., 2010a). It appears that the levels of SO_4^{2-} , NO_3^- , and NH_4^+ in PM_{10} are substantially lower in Tanzania than at European rural sites (Putaud et al., 2004) and in Asia (Aggarwal and Kawamura, 2009; Pavuluri et al., 2011).

The correlations between the calculated charge equivalent of the total cations and total anions in $PM_{2.5}$ and PM_{10} from the entire study period are shown in Fig. 7. Good correlations ($r^2 = 0.90$ for $PM_{2.5}$ and $r^2 = 0.86$ for PM_{10}) were found, indicating the measured cations (NH_4^+ , Na^+ , K^+ , Mg^{2+} and Ca^{2+}) and anions (SO_4^{2-} , NO_3^- , Cl^- , MSA^-) are well balanced during the campaigns. The slopes of the regression lines of the total cation data (in $neq\ m^{-3}$) on the total anion data (in $neq\ m^{-3}$) were 0.76 in $PM_{2.5}$ and 0.72 in PM_{10} . This indicates that the total equivalent cation concentrations are larger than those of the anions. However, it should be noted that ion chromatography did not measure carbonate and protons as well as organic anions, therefore the difference between cations and anions is thought to be attributed to these missing ions (hence the observed deviation from the slope of 1.1).

3.5 Mass concentration ratios

The mean mass ratios (and associated standard deviations) for carbonaceous materials, levoglucosan, selected aerosol components in $PM_{2.5}$ and PM_{10} are shown in Fig. 8. The levoglucosan, carbonaceous components and selected ionic species showed on average similar ratios in $PM_{2.5}$ and PM_{10} for both seasons. TC accounted for 16% and 19% of the $PM_{2.5}$ mass in wet and dry seasons, respectively, whereas in the PM_{10} mass it accounted for 13% and 15%, respectively. The OC/PM ratios in $PM_{2.5}$ were 14% and 16% whereas in PM_{10} were 12% and 13% in the wet and dry seasons, respectively. Among the carbonaceous components, OC was the most abundant, accounting for 88.7% of TC in $PM_{2.5}$ in wet season and 85.9% in dry season.

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Abundances of OC in PM₁₀ mass were 11.8 % in wet season and 13 % in dry season (Fig. 8). OC/TC ratios were 90.1 % and 87.2 % for wet and dry seasons, respectively.

In PM_{2.5}, fractions of WSOC in OC (WSOC/OC) were 72 % in wet season and 67 % in dry season whereas those of PM₁₀ in both seasons were 63 %. However, considering that biomass-burning aerosol is highly water-soluble (e.g. Kundu et al., 2010) and that secondary organic aerosol (SOA) is more hydrophilic and thus more water-soluble than primary organic matter, one would expect larger WSOC/OC ratios in dry season than in wet season. It is surprising that WSOC/OC ratios in PM_{2.5} and PM₁₀ are similar for both seasons (Fig. 8). However, as seen in Fig. 8, the production of WSOC was slightly more favourable during the wet season than in the dry season while TC to some extent was enriched with EC in dry season (i.e. 14 % compared to 11 % in PM_{2.5} and 13 % compared to 10 % in PM₁₀). This has resulted in the slightly higher mean ratio of WSOC/EC in wet season in particular for PM_{2.5}.

Water-insoluble organic carbon (WIOC), which is defined as the difference between OC and WSOC comprised a similar fraction of the TC mass in PM₁₀ during the wet and dry seasons (on average, 33 % and 32 %, respectively) whereas a relatively small difference was obtained in PM_{2.5} (25 % and 29 %, respectively). Similarly, the relative contribution of WSOC to TC in PM_{2.5} and PM₁₀ was 65 % and 57 % in wet season and 57 % and 55 % in dry season, respectively.

The observed EC/TC ratios for wet and dry seasons were 0.11 ± 0.07 and 0.14 ± 0.05 for PM_{2.5} and 0.10 ± 0.03 and 0.13 ± 0.05 for PM₁₀, respectively. These values are comparable to the average BC/TC ratios of 0.10 ± 0.03 that were reported for biomass burning aerosols in Brazil (Ferek et al., 1998) and 0.12 ± 0.07 for the Ivory Coast aerosols (Cachier et al., 1991). For biomass burning emissions, the present EC/TC ratios for both seasons could be representative of a large set of emission measurements from diverse types of biomass burning, including biofuel use (Andreae and Merlet, 2001).

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3.6 Fine (PM_{2.5}) to coarse (PM₁₀) ratios

Figure 9 shows the average percentage of PM_{2.5}/PM₁₀ ratio for the PM mass, levoglucosan, carbonaceous components and water-soluble ionic species during the wet and dry sampling campaigns. The ratios were calculated on the basis of the data for PM_{2.5} and PM₁₀ samples taken in parallel and then averaged over all samples from the campaign. The mean mass ratios of PM_{2.5}/PM₁₀ were 60 ± 17 % (range: 39 %–93 %) in wet season and 67 ± 20 % (range: 41 % to 84 %) in dry season. The results indicate that most of the PM₁₀ mass was present in the fine size fraction in both seasons. This may be due to a larger contribution from pyrogenic aerosols and photochemically produced organic aerosols, which are most likely enriched in fine (PM_{2.5}) particles and a small contribution from soil dust, which is known to be mostly associated with PM₁₀ particles. During the 2005 wet and dry season and the 2006 wet season campaigns (Mkoma et al., 2010a,b), it was found that 35 %, 49 % and 46 % of the PM₁₀ mass were present as fine particles (PM_{2.5}), which are substantially lower than the values obtained in this study. However, our present PM_{2.5}/PM₁₀ ratios are similar to those reported in rural and urban sites around the world (Gu et al., 2010; Ram and Sarin, 2011).

Average ratios of PM_{2.5} in PM₁₀ for the carbonaceous components including levoglucosan are all larger than 60 % (Fig. 9). It is also interesting to note that substantially larger PM_{2.5}/PM₁₀ ratios for WSOC (> 80 %) were obtained, which are much higher than those for OC. Possible main contributors to WSOC are biomass burning particles and secondary organic aerosol, both of which are known to be preferentially associated with the PM_{2.5} size fraction (e.g. Fuzzi et al., 2007). Figure 9 also presents high mean PM_{2.5}/PM₁₀ concentration ratios for levoglucosan (> 90 %) in the sample sets during the dry season campaign. This indicates that levoglucosan is mainly present in the fine aerosol fraction. Other studies also found similar results using other tracers or techniques (Maenhaut et al., 1996; Liu et al., 2000).

The mass concentrations of NH₄⁺, NO₃⁻ and SO₄²⁻ (i.e. typical species for inorganic secondary aerosols) reached the highest values during the dry season campaign

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(Table 1). Also, $PM_{2.5}/PM_{10}$ ratios of these species in particular SO_4^{2-} and NO_3^- increased by a factor of 1.7 and 2.8, respectively, in the dry season as compared to the wet season. Fig. 9 shows that NH_4^+ and SO_4^{2-} were mainly present in $PM_{2.5}$ in the dry season. $PM_{2.5} SO_4^{2-}$ is presumably formed by gas-to-particle conversion of anthropogenic SO_2 , but, small quantities of sulphur gases are also known to be emitted during biomass burning (Crutzen and Andreae, 1990). The study of water-soluble components in aerosols from savannah fires by Gao et al. (2003) pointed out a moderate impact for SO_4^{2-} in plumes due to a substantial quantity of SO_2 emitted. In contrast, NO_3^- was mainly associated with coarse particles during the wet season and fine particles during the dry season (Fig. 9). The NO_3^- that is associated with PM_{10} aerosols is likely derived from gas-to-particle conversion of anthropogenic NO_x during the wet season (high ambient temperatures and humidity at our site).

The sea-salt elements (Na, Mg, Cl) including the crustal element (Ca) as expected are predominantly associated with PM_{10} . The combustion of plant matter, in which K^+ is a major electrolyte within the cytoplasm, releases great quantities of K^+ -rich particles. Therefore, K^+ is an important species emitted by biomass burning and also can condense on pre-existing particles in the fine mode during the cooling of combustion emissions. In this study, K^+ was mostly associated with $PM_{2.5}$ particles, suggesting that biomass burning is an important source, especially in the dry season, when 79 % of K^+ in PM_{10} was present in the fine ($PM_{2.5}$) size fraction. Fine K^+ is a well-known biomass contributor in tropic aerosols (Maenhaut et al., 1996).

3.7 Relations between tracers and carbonaceous species: contribution from biomass burning

Water-soluble K^+ has been used as a biomass-burning indicator (Cachier et al., 1991; Andreae and Merlet, 2001), while Na^+ is generally considered as a marine proxy for sea-salt aerosol. Concentrations of Na^+ and K^+ were enhanced during the dry season, indicating that marine aerosol mixed with the biomass burning plumes was transported

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to the sampling site by the southeasterly wind which is predominant during this season. The nss-SO₄²⁻ and nss-K⁺ were obtained by subtracting the sea-salt contribution from the measured SO₄²⁻ and K⁺ data sets. The sea-salt contribution of SO₄²⁻ and K⁺ were obtained as 0.252(Na⁺) and 0.0355(Na⁺). (Na⁺) is the concentration of measured Na⁺ and 0.252 and 0.0355 are the SO₄²⁻/Na⁺ and K⁺/Na⁺ ratios, respectively, in bulk sea-water composition given by Riley and Chester (1971). The water-soluble Na⁺ in the PM was assumed to be derived from sea-salts only.

$$(\text{nss-SO}_4^{2-}) = (\text{SO}_4^{2-}) - 0.252(\text{Na}^+) \quad (1)$$

$$(\text{nss-K}^+) = (\text{K}^+) - 0.0355(\text{Na}^+), \quad (2)$$

where the water-soluble K⁺ is assumed to be related to biomass combustion (Cachier et al., 1991), and the contribution of leachable K⁺ from dust materials is negligible.

The nss-K⁺ concentrations in PM_{2.5} and PM₁₀ during the sampling period are shown in Table 1. The nss-K⁺ accounts for total water-soluble K⁺ (nss-K⁺/K⁺ ratio) in a range between 92 % and 98 % for PM_{2.5} and PM₁₀ during the campaigns. This suggests that K⁺ from sea-salt was not important in PM_{2.5} or PM₁₀ fractions, indicating that sea-salts from the Indian Ocean exert little influence on the Morogoro atmosphere at least during the sampling period. The high concentrations of nss-K⁺ in PM_{2.5} are consistent with particulate K associated with the emissions from biomass burning rather than sea-salt contribution. The sea-salts are also the minor carrier of particulate SO₄²⁻ among PM_{2.5} aerosol particles due to the high ratios of nss-SO₄²⁻ to SO₄²⁻ (average 60 %, Fig. 8).

Biomass burning sources are generally characterized by high K⁺ contents (Cachier et al., 1991; Andreae and Merlet, 2001). K⁺/OC ratios could be an indicator to distinguish biomass burning from other OC sources. The nss-K⁺/OC ratios in Morogoro varied from 0.06–0.36 in PM_{2.5} and from 0.03–0.34 in PM₁₀ aerosols. These ratios are comparable to or higher than K⁺/OC ratios reported for Savannah burning (0.08–0.10) (Echalar et al., 1995) as well as tropical forest (0.06) and agricultural residues burning (0.04–0.13) calculated from emission factors (Andreae and Merlet, 2001).

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As expected, slightly higher $\text{nss-K}^+/\text{OC}$ ratios were observed in July–August (dry season), about a factor of 2 higher than the ratio in wet season (Fig. 10). This is interesting because in spite of the different concentration levels between $\text{PM}_{2.5}$ and PM_{10} the two fractions exhibit almost the same sensitivity to biomass burning. A good correlation was obtained between nss-K^+ and OC especially in dry season for both $\text{PM}_{2.5}$ ($r^2 = 0.67$) and PM_{10} ($r^2 = 0.74$) (Figure not shown). These results are interesting because PM_{10} samples showed a somewhat stronger correlation between nss-K^+ and OC than $\text{PM}_{2.5}$ in which biomass burning smoke particles are more enriched (Engling et al., 2006, 2011; Herckes et al., 2006).

On the other hand, the mean $\text{nss-K}^+/\text{EC}$ ratios were 0.90 ± 0.33 and 1.60 ± 0.54 in $\text{PM}_{2.5}$ and 0.99 ± 0.54 and 1.76 ± 1.03 in PM_{10} for the wet and dry seasons, respectively. These ratios are about 2 to 3 times higher than K/BC (K^+/EC) ratios reported for biomass burning (0.52 ± 0.11) in Brazil (Ferek et al., 1998) and (0.44 ± 0.11) in Northern India (Ram and Sarin, 2010). The $\text{nss-K}^+/\text{EC}$ ratios observed in this study are higher than those from emission factors reported by Andreae and Merelet (2001) for tropical forest (average 0.44) and the burning of agricultural residues (average 0.19). Further, the ratios are much higher than that reported in Christchurch, New Zealand (average 0.05), where wood and coal burning were considered as major sources of domestic energy (Wang et al., 2005). The higher $\text{nss-K}^+/\text{EC}$ ratios obtained in Tanzania may be associated with the unique character of biomass burning in the region.

Nss-SO_4^{2-} to EC ratios in $\text{PM}_{2.5}$ were 0.32 ± 0.20 (range: 0.13–0.83) in wet season and 0.29 ± 0.13 (range: 0.12–0.48) in dry season. $\text{Nss-SO}_4^{2-}/\text{TC}$ ratios in $\text{PM}_{2.5}$ ranged from 0.01 to 0.05 with an average of 0.03 in wet season and 0.04 in dry season. These values are comparable to $\text{SO}_4^{2-}/\text{BC}$ (0.28 ± 0.13) and $\text{SO}_4^{2-}/\text{TC}$ (0.03 ± 0.01) ratios reported in Brazilian biomass smoke (Ferek et al., 1998), but $\text{PM}_{2.5}$ $\text{nss-SO}_4^{2-}/\text{EC}$ ratio are 3 times higher than the ratios (0.09) from road tunnel aerosols (Gillies et al., 2001). It should be noted that during our campaigns the $\text{nss-SO}_4^{2-}/\text{OC}$ ratio in $\text{PM}_{2.5}$ ranged from 0.01–0.06 (average 0.04 ± 0.02). $\text{PM}_{2.5}$ NO_3^-/OC (0.18 ± 0.13 wet, and 0.23 ± 0.13 dry) ratios are twice that (0.1) reported in road tunnel aerosols (Gillies et al., 2001). All

these comparisons for mass concentration ratios suggest that Morogoro aerosols are mostly influenced by biomass/biofuel burning rather than fossil fuel combustion.

The concentrations between biomass marker species (levoglucosan and nss-K⁺) with WSOC and OC were also examined to determine the source strength of biomass/biofuel burning. During the dry season, levoglucosan showed a good correlation with nss-K⁺ in PM_{2.5} ($r^2 = 0.67$) and PM₁₀ ($r^2 = 0.57$) (Fig. 11a, b). These concentrations suggest that biomass burning contributed to the particulate K (in addition EC was emitted from biofuels) in the dry season. Levoglucosan, also positively correlates with WSOC ($r^2 = 0.60$) and OC ($r^2 = 0.75$) in PM_{2.5} especially in dry season (Fig. 11c). Strong relations were found for WSOC and OC with levoglucosan in PM₁₀ especially in the dry season. These results suggest that emissions from biomass burning significantly contribute to WSOC and OC during the campaigns. A positive correlation ($r^2 = 0.54$) was found between WSOC and nss-K⁺ in PM_{2.5} during the dry season. In the wet season, no correlation (PM_{2.5}) and poor correlation (PM₁₀) were observed between WSOC and nss-K⁺. This study demonstrates that biomass burning is an important source of organic aerosols in rural Tanzania during the dry season.

3.8 Contributions of biomass burning to OC

Table 2 shows concentrations of biomass burning tracers levoglucosan (LG) and mannosan (MN), ratios of LG to MN and the contribution of levoglucosan to OC. The LG/MN ratios were found to be fairly high, ranging from 9.8 to 13.0 in PM_{2.5} and from 8.9–12.7 in PM₁₀ (Table 2). These higher LG/MN ratios suggest that the biomass burning tracers are mainly associated with burning of biofuels, agricultural residues and open fires. It is of interest to note that these values are comparable to or lower than those observed at rural and background sites in Asia where fuel wood (as main energy source) and biomass burning smoke from agricultural residues have greater influence (Fu et al., 2008; Zhang et al., 2012). On the other hand our PM_{2.5} LG/MN ratio is higher than those reported from residential burning and forest fires in Maine, United State of America (Medeiros et al., 2006), Aveiro, Portugal (Pio et al., 2008) and Rondônia, Brazil

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(Decesari et al., 2006). This comparison suggests larger influence of smoke aerosol derived from grass-type fuels (such as crop residues) and/or hard wood than from burning of softwood in the sampling site of Tanzania.

The contributions of biomass smoke to total ambient OC in PM_{2.5} and PM₁₀ at Morogoro can be estimated using the measured levoglucosan and OC values. For precise estimates of biomass burning contributions in the study area, the use of emission factors that are representative of the actual processes is vital. However, in Tanzania and the East African region, emission factors of molecular tracers (e.g. levoglucosan) for biomass burning are lacking. It is clear that the chemical properties of organic aerosol derived from biomass burning vary depending on the type of original biomass (such as agricultural waste, cereal straw, vegetation, wood) and the combustion conditions (Hays et al., 2005; Engling et al., 2006; Zhang et al., 2007; Fu et al., 2008; Medeiros and Simoneit, 2008; Schmidl et al., 2008). Wood and charcoal fuels are commonly used for domestic cooking in Tanzania. In addition to our sampling site, the burning of agricultural residue such as cereal straws (e.g. corn straws) may be considered.

The ratios of levoglucosan to OC (LG/OC) in aerosol have been used to indicate biomass burning source contributions (e.g. Zhang et al., 2008). In this study, the mean LG/OC ratios in the wet and dry seasons were 3.9% and 4.2% in PM_{2.5} and 3.5% and 3.8% in PM₁₀, respectively (Table 2). It is noteworthy that mean contributions of levoglucosan to OC were high in the dry season, when biomass burning tracer concentrations are enhanced. These values are comparable to or lower than reported LG/OC ratios from biomass combustion studies elsewhere (Mazzoleni et al., 2007; Zhang et al., 2008, 2012), suggesting that biomass burning largely influence the air quality at our rural site in Tanzania. Wood and agricultural waste burning (including corn straw that is common at our site) could also be an important contributor to the observed levels of OC.

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4 Summary and conclusions

In this study, the impacts of biomass burning and other emission sources on atmospheric aerosols ($PM_{2.5}$ and PM_{10}) have been investigated during the wet and dry seasons in Tanzania, East Africa. Here we measured OC/EC, WSOC, biomass burning tracer (levoglucosan and mannosan) and major water-soluble inorganic ions at a rural background site in Morogoro during the wet and dry seasons. The results show that concentrations of biomass burning tracers such as levoglucosan and water-soluble K^+ were found to be higher in the dry season. Water-soluble K^+ was the most abundant cation whereas SO_4^{2-} was the main anionic species in $PM_{2.5}$. In contrast, Na^+ and Ca^{2+} were the most abundant cations and SO_4^{2-} the main anionic species in PM_{10} . Levoglucosan, a unique biomass-burning tracer, showed a good correlation with $nss-K^+$ in $PM_{2.5}$ and PM_{10} in particular during the dry season. This biomass burning tracer positively correlated with WSOC and OC in $PM_{2.5}$ in wet season. Levoglucosan accounted for 3.9% and 4.2% in $PM_{2.5}$ and 3.5% and 3.8% in PM_{10} of OC in the wet and dry seasons, respectively. This study demonstrates that biomass and biofuel burning activities including forest/open fires and burning of agricultural residues, as well as secondary aerosol formation, could have a significant impact on the remote and urban air quality in the Tanzanian atmosphere. This study also provides, for the first time, the baseline data for biomass marker species (i.e. levoglucosan) for the Eastern and Southern African region, where biomass and biofuel burning including forest fires could influence regional and global climate. These findings also indicate the necessity to implement policies regarding the control of biomass/biofuel use in Tanzania and other parts of the African region.

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Table 1. Mean concentrations and ranges of the PM mass, levoglucosan, carbonaceous components and major inorganic ions in PM_{2.5} and PM₁₀ during the 2011 wet and dry seasons in Morogoro.

Component/species	PM _{2.5}				PM ₁₀			
	Wet season (<i>n</i> = 11)		Dry season (<i>n</i> = 10)		Wet season (<i>n</i> = 11)		Dry season (<i>n</i> = 10)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
PM (μg m ⁻³) and organic components (μg C m ⁻³)								
PM	16.6–38.2	28.2 ± 6.4	29.8–61.3	39.1 ± 9.8	35.7–57.3	47 ± 8.2	36.8–99.5	61.4 ± 19.2
TC	2.6–7.2	4.4 ± 1.4	4.6–9.8	7.0 ± 1.9	3.4–9.9	6.3 ± 1.8	4.2–16.3	9.3 ± 4.1
OC	2.0–6.1	3.9 ± 1.3	3.4–8.5	6.0 ± 1.7	3.1–8.2	5.6 ± 1.4	4.0–13.8	7.9 ± 3.1
EC	0.2–1.1	0.5 ± 0.3	0.5–1.4	1.0 ± 0.3	0.2–1.7	0.7 ± 0.4	0.2–3.7	1.3 ± 1.0
WSOC	1.4–4.6	3.0 ± 1.0	2.5–5.0	3.9 ± 0.9	2.3–4.4	3.5 ± 0.6	2.8–7.4	4.8 ± 1.4
Levoglucosan (ng m ⁻³)	38–307.6	145.8 ± 85.2	138–408.2	252.8 ± 77.5	49.5–376.7	209.2 ± 95.1	98.6–658.9	307.6 ± 154
Inorganic ions (ng m ⁻³)								
NH ₄ ⁺	40.7–458	210 ± 122	325–2344	928 ± 669	75.8–628	207 ± 180	96.7–1400	654 ± 432
NO ₃ ⁻	42.7–136	64.4 ± 27.1	114–264	180 ± 54.7	93.3–248	172 ± 56	172–774	440 ± 209
SO ₄ ²⁻	71.7–376	214 ± 75.1	59.9–560	261 ± 189	183–511	294 ± 92	321–1135	585 ± 280
nss-SO ₄ ²⁻	28.7–328	133 ± 97.5	139–439	244 ± 125	15.9–324	73.8 ± 102	85.3–409	280 ± 139
Cl ⁻	39.1–99.4	62.5 ± 22.1	35.1–175	80.4 ± 50.1	73.5–602	183 ± 148	46.9–656	328 ± 200
MSA ⁻	7.7–35.1	16.2 ± 7.0	11.5–26.5	17.6 ± 4.3	8.1–20.8	13.5 ± 4.2	13.1–49.8	27.7 ± 11.8
Na ⁺	126–568	320 ± 117	378.4–937	621 ± 154	529–2913	1145 ± 681	386–4349	2243 ± 1279
Mg ²⁺	6.1–263	94.4 ± 86.3	12.5–146	79 ± 60.8	65.2–580	239 ± 150	4.8–985	460 ± 334
K ⁺	167–741	393 ± 169	715–2710	1538 ± 702	170–1683	632 ± 406	922–3788	1909 ± 1089
nss-K ⁺	156–734	382 ± 170	691–2688	1516 ± 703	149–1657	591 ± 408	851–3669	1829 ± 1053
Ca ²⁺	39.1–99.4	62.5 ± 22.1	111–608	297 ± 153	594–1948	1272 ± 416	532–3529	1702 ± 1074

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Table 2. Mean concentrations of levoglucosan and mannosan (ng m^{-3}), levoglucosan/mannosan (LG/MN) ratios and contribution of levoglucosan to OC (%) in $\text{PM}_{2.5}$ and PM_{10} during the 2011 wet and dry seasons in Morogoro.

Season/size	Levoglucosan	Mannosan	LG/MN		LG/OC ratio (%)	
	Mean \pm SD	Mean \pm SD	Range	Mean \pm SD	Range	Mean \pm SD
PM _{2.5} size fraction						
Wet	145.8 \pm 85.2	12.7 \pm 7.3	10.6–13.0	11.5 \pm 0.8	0.8–10.5	3.9 \pm 2.6
Dry	252.8 \pm 77.5	23.6 \pm 7.4	9.8–12.9	10.8 \pm 1.1	2.9–5.0	4.2 \pm 0.6
PM ₁₀ size fraction						
Wet	209.2 \pm 95.1	20.0 \pm 8.9	8.9–11.7	10.4 \pm 0.8	1.6–5.5	3.5 \pm 1.0
Dry	307.6 \pm 154	29.9 \pm 14.5	9.1–12.7	10.4 \pm 1.1	2.5–4.8	3.8 \pm 0.6

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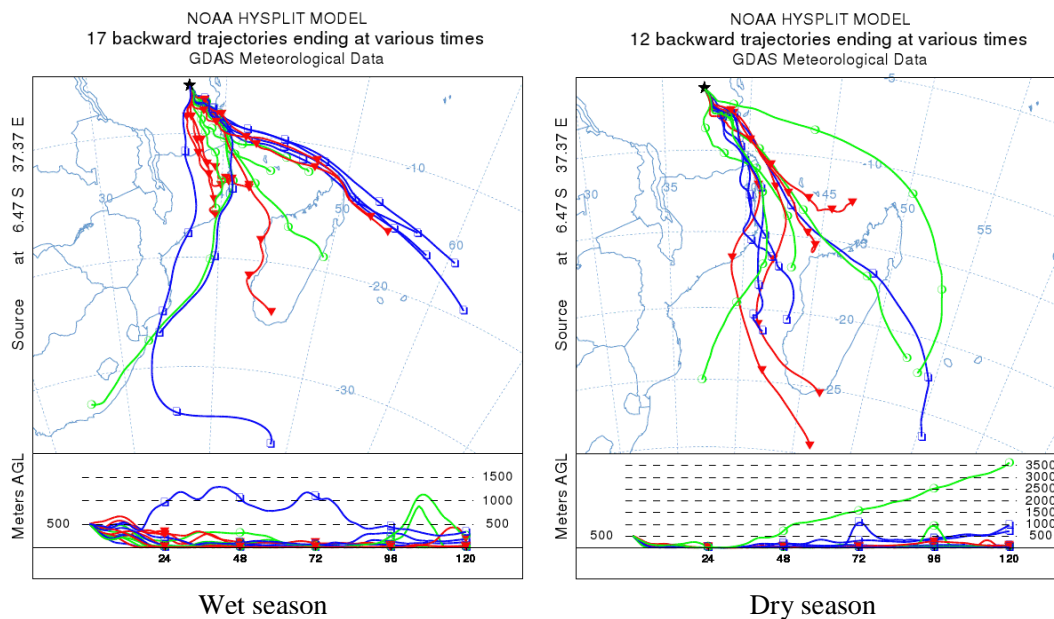


Fig. 1. Five-day backward air mass trajectories arriving at Morogoro during the sampling period.

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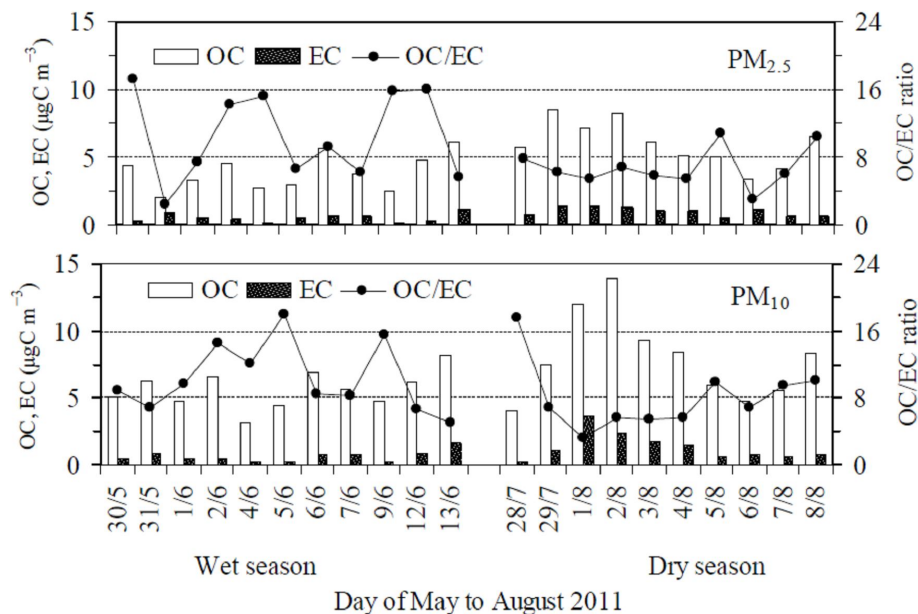


Fig. 2. Temporal variations of concentrations of OC and EC and OC/EC ratios at Morogoro during the wet and dry seasons in PM_{2.5} and PM₁₀.

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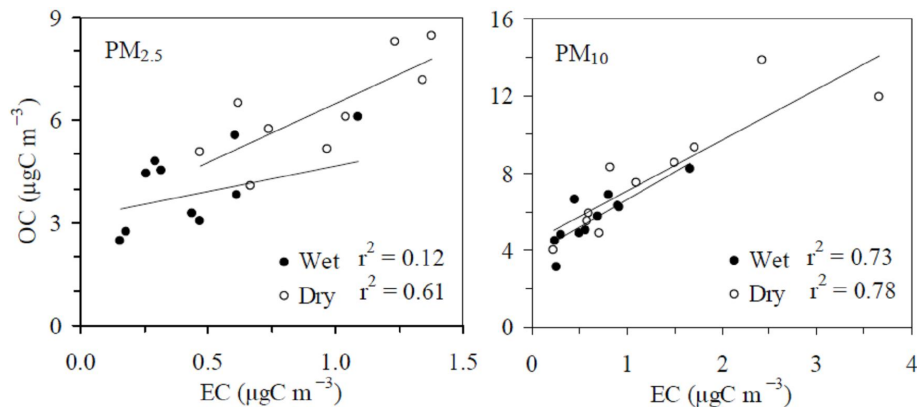


Fig. 3. Relations between OC and EC in PM_{2.5} and PM₁₀ during the wet and dry seasons in Morogoro.

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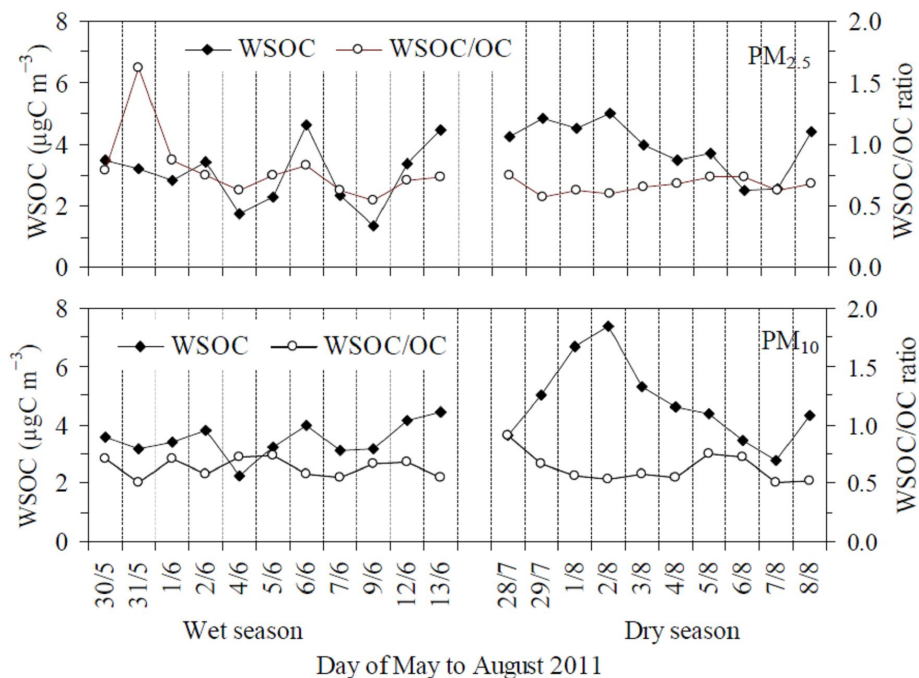


Fig. 4. Temporal variations of concentrations of WSOC and WSOC/OC ratios at Morogoro during the wet and dry seasons for $PM_{2.5}$ and PM_{10} .

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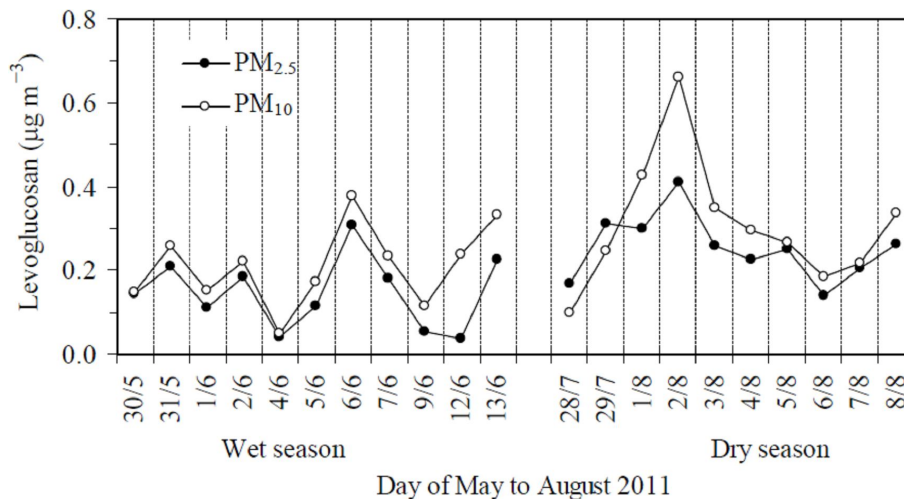


Fig. 5. Temporal variations of levoglucosan in PM_{2.5} and PM₁₀ at Morogoro during the wet and dry seasons.

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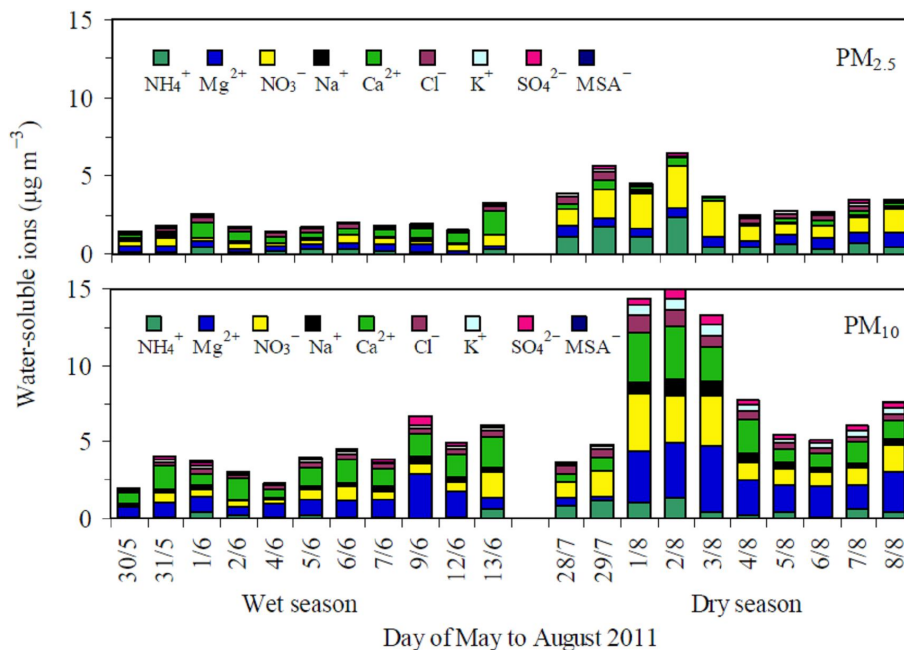


Fig. 6. Time series of water-soluble inorganic ions in PM_{2.5} and PM₁₀ during the wet and dry seasons.

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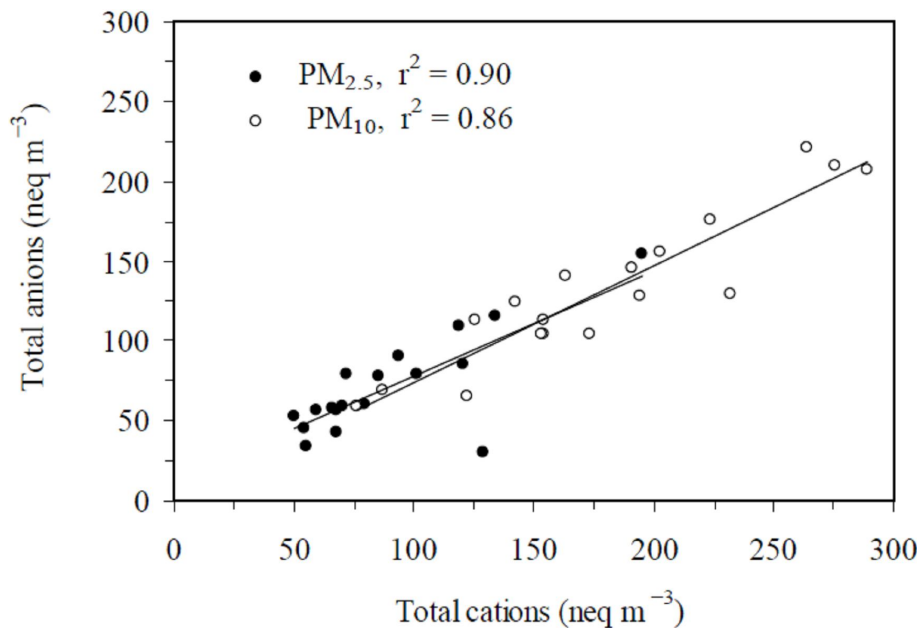


Fig. 7. Relations between total cations and anions in $PM_{2.5}$ and PM_{10} from Morogoro during the sampling period.

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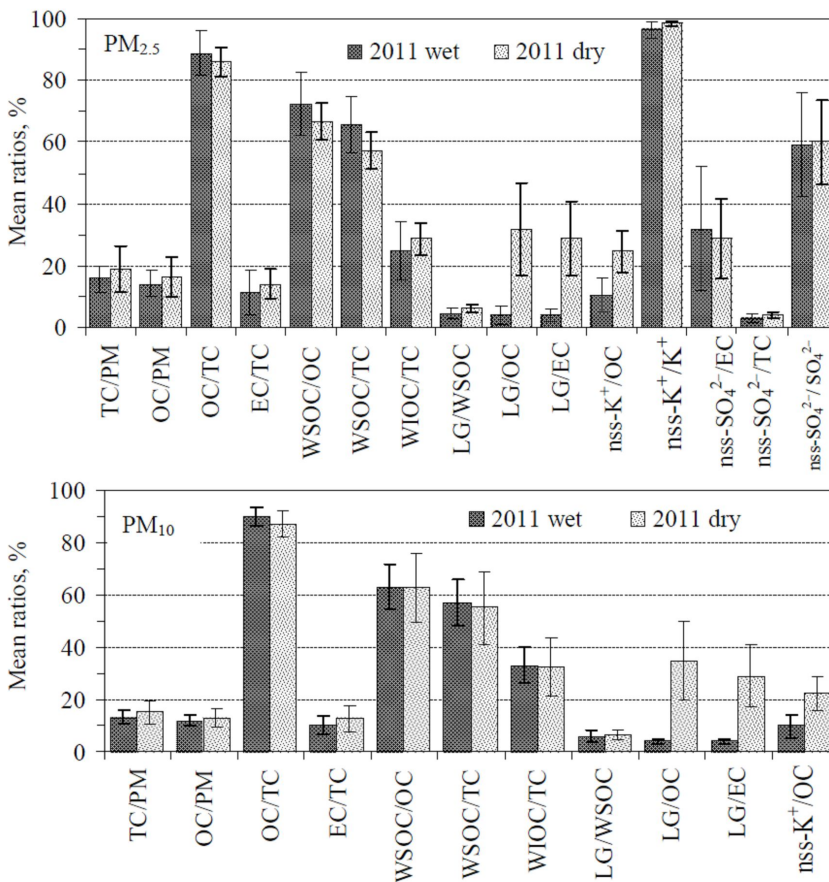


Fig. 8. Mean mass concentration ratios (and associated standard deviations) for selected aerosol species in PM_{2.5} and PM₁₀ during the 2011 wet and dry seasons in Morogoro.

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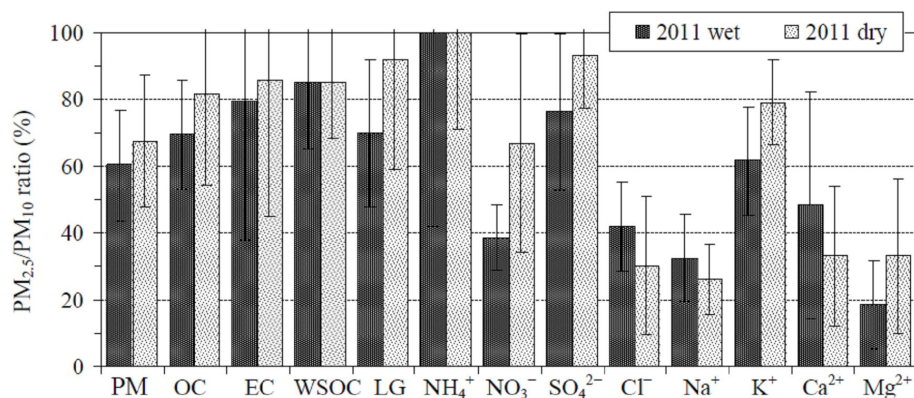


Fig. 9. Mean concentration ratios (%) of selected aerosol components or species in $PM_{2.5}$ to those in PM_{10} during the 2011 wet and dry season campaigns in Morogoro.

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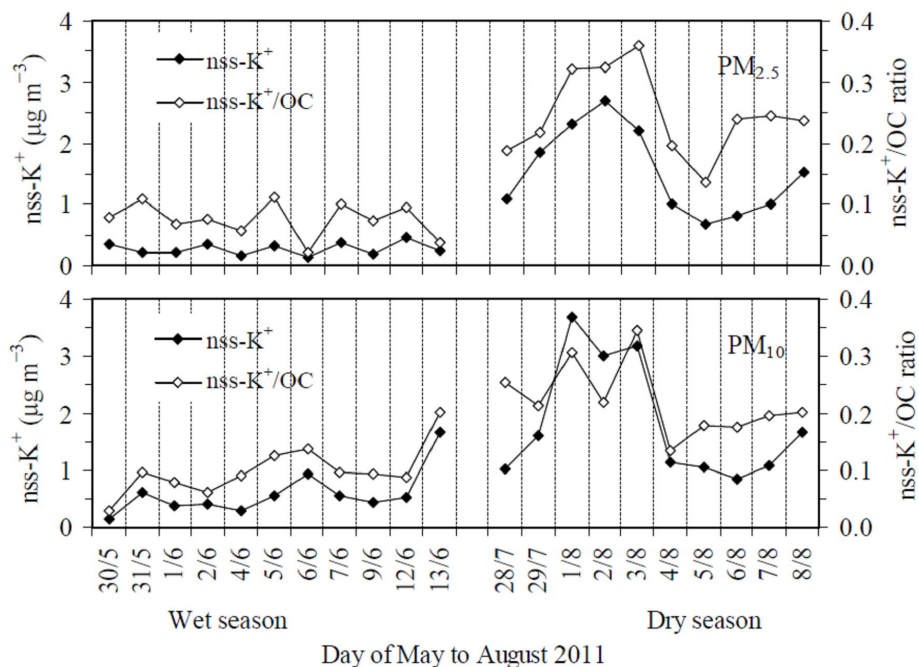


Fig. 10. Temporal variations of nss-K^+ and $\text{nss-K}^+/\text{OC}$ ratios in $\text{PM}_{2.5}$ and PM_{10} during the wet and dry seasons.

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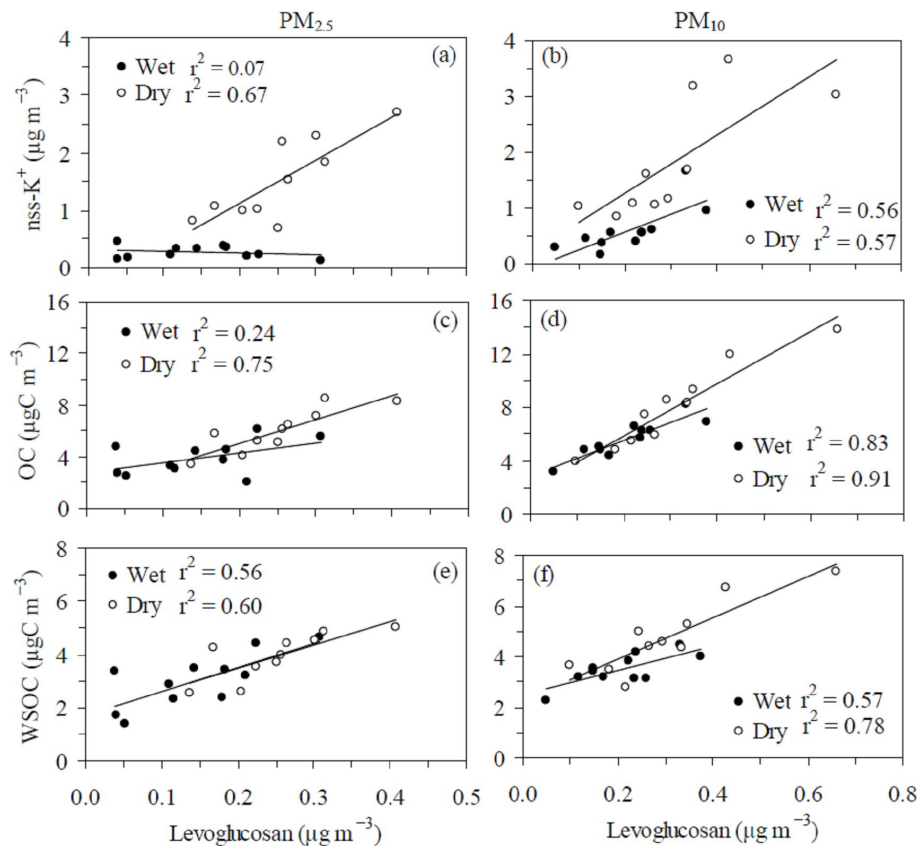


Fig. 11. The relationship between levoglucosan with nss-K⁺, OC and WSOC in PM_{2.5} (a, c, e) and PM₁₀ (b, d, f) at Morogoro during the wet and dry seasons.

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