Atmospheric Pollution Research 2 (2011) 126-137

Atmospheric Pollution Research

www.atmospolres.com

Air particulate matter pollution in Ulaanbaatar, Mongolia: determination of composition, source contributions and source locations

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ABSTRACT

Ulaanbaatar, the capital city of Mongolia is subject to high air particulate matter pollution episodes during winter and during dust storm events in spring and autumn that have severe implications for the health of the exposed population. This paper presents the results of fine ($PM_{2.5}$) and coarse ($PM_{10–2.5}$) particulate matter monitoring in Ulaanbaatar from 2004 to 2008 and receptor modelling to determine the sources contributing to particulate matter pollution. Ion Beam Analysis was used to determine elemental concentrations in the two size fractions and black carbon was measured with a light reflectance device. Mass contributions to ambient particle concentrations from emission sources were estimated by positive matrix factorisation and air mass back–trajectory analysis was used to assess probable source locations. The results show that crustal matter sources are the primary contributors to the coarse particle fraction. Combustion sources (coal combustion, biomass burning, and motor vehicles) dominate the fine fraction of particulate matter in the Ulaanbaatar airshed, primarily from local emission sources but forest fires to the north can be a significant contributor to biomass burning concentrations at times. Analysis of seasonal differences showed that coal combustion processes were largely responsible for fine particle air pollution episodes during winter. Temporal trends show an increase in the coal combustion contributions over the monitoring period. We suggest that this is linked to the increase in the Ulaanbaatar population and a consequent increase in the use of coal for power generation and domestic heating purposes.

Keywords:
Air pollution
Particulate matter
IBA
Positive matrix factorisation
Receptor modelling
Mongolia

Article History:
Received: 27 May 2010
Revised: 25 August 2010
Accepted: 09 September 2010

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doi: 10.5094/APR.2011.017

1. Introduction

This paper presents the results of air particulate matter sampling from October 2004 to April 2008 at Ulaanbaatar, the capital city of Mongolia (Figure 1). The monitoring in Ulaanbaatar was part of a wider programme run under the auspices of the International Atomic Energy Agency (IAEA) (Markwitz 2005; Hopke et al., 2008). Ulaanbaatar (population 1 million) is situated in a large dome valley surrounded by mountains and subject to freezing conditions and temperature inversions during winter months (December–February). This work presents $PM_{2.5}$ and $PM_{10–2.5}$ monitoring results and receptor modelling using positive matrix factorisation (PMF) to apportion source contributions to each of the size fractions. Air particulate matter pollution in Ulaanbaatar can be extreme at times with both $PM_{2.5}$ or $PM_{10–2.5}$ exceeding 200 µg m^{-3}.

A number of emission inventories have been prepared for the Ulaanbaatar airshed (NAMHEM, 2007; Guttikunda, 2007) in order to quantify source emissions and contributions to particulate matter air pollution in the city. However, some sources such as fugitive dust from dust storms and local dust generating activities or emissions from domestic use of fuels for heating and cooking are difficult to quantify per se or the emissions factors and activity estimates have a high uncertainty associated (>50%). The receptor modelling approach fills these knowledge gaps and provides information on the key sources contributing to particulate matter concentrations in Ulaanbaatar.

2. Experimental

2.1. Sample collection and analytical methods

$PM_{2.5}$ and $PM_{10–2.5}$ samples were collected on a two–day–per–week basis (Mondays and Wednesdays) from October 2004 to April 2008 at the National University of Mongolia air quality monitoring site, 4 kilometers east of the centre of Ulaanbaatar as shown in Figure 1b (latitude 47 914 deg, longitude 106 972 deg, 1 300 m above sea level). The fine and coarse particle size fractions were collected with a GENT sampler (Maenhaut et al., 1993). The sampler consists of a PM_{10} impactor–type size selective inlet and stacked filter unit assembly connected to a pump and gas meter. The stacked filter unit (SFU) is made up of two filters in series, the top filter (polycarbonate) collects the particulate size fraction between 10 microns and 2.5 microns in aerodynamic diameter ($PM_{10–2.5}$ or coarse fraction), the bottom filter (polycarbonate) collects particulate matter 2.5 microns and less in aerodynamic diameter ($PM_{2.5}$ or fine fraction). The performance of the SFU and the size selective inlet has been assessed against other particle monitoring systems (Hopke et al., 1997). Generally, the samples

Figure 1. *Map showing* ***(a)*** *Ulaanbaatar, Mongolia and* ***(b)*** *location of monitoring site in Ulaanbaatar (★). Source: Google Earth (www.google.com).*

were collected for a 24 hour period, but on some days it was not possible to collect the sample over the entire 24 hours as the high particulate matter concentrations lead to filter clogging. Thus, the sampler was operated alternating time on and time off (e.g., 1 h on followed by 1 h off) over the course of the 24 hours period to provide a representative sample for that day. Gravimetric analysis was carried out at the National University of Mongolia, Ulaanbaatar and results reported as micrograms of particulate matter per cubic metre of air sampled (LOD ~ 5 μg m^{-3}; uncertainty estimated at ± 10%).

Ion Beam Analysis (IBA) was used to measure the concentrations of elements with atomic number above neon in particulate matter on the size–resolved filter samples from Ulaanbaatar. IBA measurements for this study were carried out at the New Zealand IBA Facility operated by the Institute of Geological and Nuclear Sciences (GNS) in Gracefield, Lower Hutt (Trompetter et al., 2005).

Black carbon (BC) concentrations on filters were determined by light reflection using a M43D Digital Smoke Stain Reflectometer. Black carbon has been studied extensively but it is still not clear to what extent it is either elemental carbon [graphitic, C(0)], high molecular weight refractory weight organic species or a combination of both (Jacobson et al., 2000). For combustion sources such as petrol and diesel fuelled vehicles and biomass burning elemental (or graphitic carbon) and organic carbon compounds (OC) are the principle aerosol components emitted (Jacobson et al., 2000; Fine et al., 2001; Watson et al., 2002; Salma et al., 2004). The absorption and reflection of visible light on particles in the atmosphere or collected on filters is dependent on the particle concentration, density, refractive index and size. For atmospheric particles, BC is the most highly absorbing component in the visible light spectrum with very much smaller absorption coming from soil, sulphate and nitrate (Horvath, 1993; Horvath, 1997). Hence, to the first order it is assumed for the purposes of this study that all the light absorption by particles on filters is due to BC.

2.2. Receptor modelling

Receptor modelling and apportionment of PM mass by PMF was performed using the PMF2 program (Paatero, 1997). With PMF, sources are constrained to have non–negative species concentrations, no sample can have a negative source contribution and error estimates for each observed data point are used as point–by–point weights. This feature is a distinct advantage, in that it can accommodate missing and below detection limit data that is a common feature of environmental monitoring results (Song et al., 2001). The signal–to–noise ratio for an individual elemental measurement can have a significant influence on a receptor model and modelling results. For the weakest (closest to detection limit) species the variance may be entirely due to noise (Paatero and Hopke, 2002). Paatero and Hopke (2003) strongly suggest down–weighting or discarding noisy variables (as measured by their signal–to–noise ratio) that are always below their detection limit or species that have a lot of uncertainty in their measurements relative to the magnitude of their concentrations. Therefore the data were screened by their signal–to–noise ratio (S/N ratio). Variables with very low S/N ratios (≤ 0.2) were excluded from the analysis, while weak variables (0.2 ≤ S/N ≤ 2) were down–weighted. Rotational freedom in solutions were explored and controlled using FPEAK (Paatero and Hopke, 2002) and observing the effect on the Q values (chi–squared), G–vector plots and residual plots (Paatero et al., 2005). Only those solutions that could be related to physical sources were considered acceptable.

2.3. Back trajectories and potential source contribution function analysis

The HYSPLIT (HYbrid Single–Particle Lagrangian Integrated Trajectory) model is the newest version of a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations (Draxler and Rolph, 2003). Using a global meteorological dataset HYSPLIT computes the advection of a single pollutant particle, or simply its trajectory. For the purpose of this study, HYSPLIT has been used to calculate the 96–hour back trajectories of air parcels for sample days of interest in order to examine long–range atmospheric transport processes and determine potential particulate matter source locations. The potential source contribution function (PSCF) analysis calculates the probable source locations for those sources considered to be impacting at a receptor site from long–range transport of pollutants. If a trajectory endpoint lies in the ij^{th} cell, the air parcel

assumes to collect PM emitted in the cell and transports along the trajectory to the monitoring site. $PSCF_{ij}$ is the conditional probability that an air parcel that passed through the ij^{th} cell had a high concentration upon arrival at the monitoring site:

$$PSCF_{ij} = \frac{m_{ij}}{n_{ij}} \quad (1)$$

where n_{ij} is the total number of end points that fall in the ij^{th} cell, m_{ij} is the number of end points that exceeded the threshold criterion (in this study, the average concentration of each species was used for the threshold criterion).

PSCF describes the spatial distribution of probable geographical source locations. Grid cells which have high PSCF values are the potential source areas whose emissions are likely to contribute to particulate matter concentrations at the monitoring site. For a secondary aerosol pollutant, a high PSCF area may also include areas where secondary particle formation is enhanced (Begum et al., 2005).

3. Results and Discussion

3.1. Particulate matter concentrations in Ulaanbaatar

Coarse and fine particle concentrations were combined to provide a measure of ambient PM_{10} concentrations at Ulaanbaatar (Figure 2a). Particulate matter concentrations were found to be dominated by the coarse fraction (Figure 2b) which were higher during spring (March – May) and autumn (September – November). Fine particle concentrations peaked during winter (December – February). Note that no monitoring was carried out during the summer (April – August) of 2005.

Particulate matter concentrations were found to be extremely high at times with maximum PM_{10} concentrations measured at 1 100 µg m^{-3} and many days where concentrations were above 300 µg m^{-3}, however, there may be some uncertainty in the GENT gravimetric mass at such extreme concentrations (i.e. > 600 µg m^{-3}) due to the potential for filter clogging. The coarse particle fraction generally dominated PM_{10} but high $PM_{2.5}$ values were recorded during winter months with $PM_{2.5}$ values often over 100 µg m^{-3}. With such high particulate matter concentrations present in the Ulaanbaatar urban area there are likely to be significant health implications for the exposed population.

3.2. $PM_{10–2.5}$ data analysis

A total of 224 (91% of total samples collected) particulate matter samples were included in the receptor modelling analyses of Ulaanbaatar coarse particle data. While more than 25 elemental constituents were detected above their respective LOD, 16 species were selected for PMF modelling ($PM_{10–2.5}$, BC, Na , Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn) as other elements were only present in a few samples and/or the S/N ratio was lower than 0.2. Table 1 presents the mean, standard deviation, median, maximum, minimum, and number of samples above LOD and S/N ratio for individual species.

Different source numbers (3-9) were used for deriving PMF solutions and the effects on the *Q* values (and *Q* value as a function of FPEAK), residual matrices and *G*-space plots were observed to determine the optimal number of primary contributing sources to ambient coarse particle concentrations. The measured coarse mass was included as an independent variable in PMF modelling to circumvent the need for multiple linear regression to apportion mass (Kim and Hopke, 2006). The derived source profiles were compared to measured source profiles and/or those reported in other studies to ensure they made physical sense. A four-source model was found to be the most appropriate solution (FPEAK = -0.2) which, on average explained 86% of the gravimetric mass. Figure 3 shows the comparison (r^2 = 0.88) between predicted (PMF) $PM_{10–2.5}$ and measured (gravimetric) $PM_{10–2.5}$ concentrations. The average mass contributions of each of the sources to ambient coarse particle concentrations are shown in Table 2 and the elemental source profiles are presented in Figure 4.

The first source profile was identified as airborne soil originating from crustal matter as the profile is dominated by Al and Si along with Ca, Ti and Fe. The Si:Al ratio was found to be 2.6:1, typical of crustal matter composition (aluminosilicates) (Lide, 1992). A second crustal matter source, labelled as Soil 2, has also been identified as originating from crustal matter and the primary distinction between the two soil profiles is that the Soil 2 source has a significantly higher BC component. We suggest that the difference between the two crustal matter sources is most likely

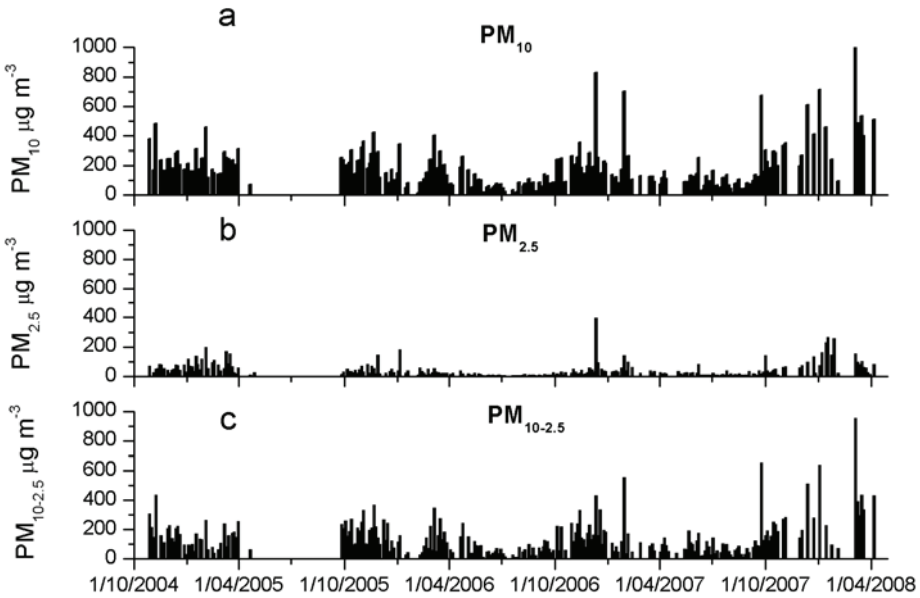

Figure 2. *Particulate matter concentrations at Ulaanbaatar: (a) PM_{10}; (b) $PM_{2.5}$; (c) $PM_{10–2.5}$.*

Table 1. *Summary statistics for $PM_{10-2.5}$ and elemental concentrations at Ulaanbaatar*

ng m^{-3}	Arithmetic Mean	StdDev	Median	Maximum	Minimum	LOD	# Samples > LOD[a]	S/N
$PM_{10-2.5}$	143 000	122 000	110 000	955 000	5 000	-	-	-
BC	4 401	3 394	3 550	25 617	483	300	224	3.1
Na	843	829	614	4 434	0	400	173	0.3
Mg	936	769	736	4 781	70	72	195	0.5
Al	5 524	4 832	3 800	23 436	191	40	223	3.4
Si	13 579	10 877	10 696	61 060	507	30	224	26.0
P	211	285	130	2 087	0	61	189	0.6
S	1 458	1 659	965	13 831	129	30	224	15.1
Cl	331	244	264	1 284	34	27	224	6.0
K	1 760	1 441	1 340	7 813	72	25	224	18.0
Ca	4 604	3 443	3 616	20 023	257	25	224	20.6
Ti	298	324	197	2 981	7	17	224	8.1
Mn	80	66	60	364	3	14	224	3.1
Fe	3 338	2 707	2 493	14 214	116	16	224	1.0
Cu	21	38	9	372	0	18	126	0.4
Zn	99	180	58	2 415	0	16	211	2.5

[a] *Limit of detection*

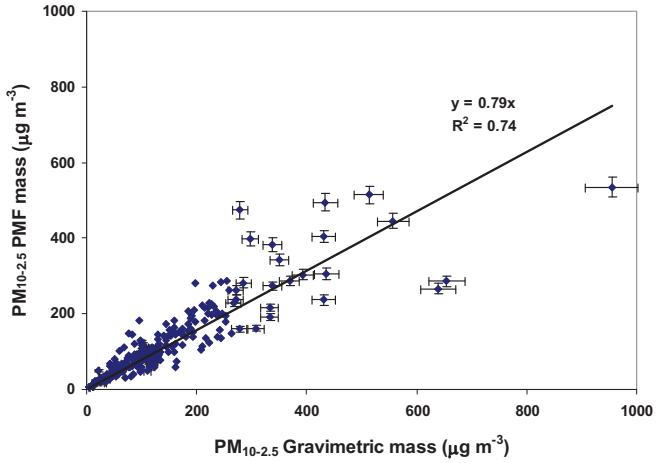

Figure 3. *Plot of predicted (PMF) $PM_{10-2.5}$ mass concentrations versus measured (gravimetric) $PM_{10-2.5}$ mass concentrations.*

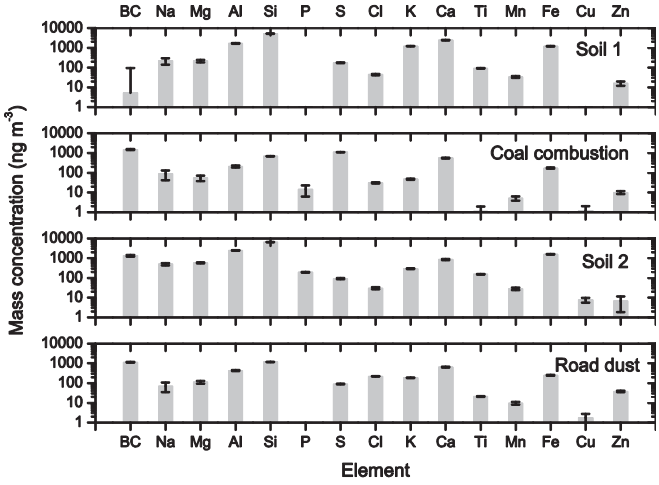

Figure 4. *Elemental source profiles derived by PMF for $PM_{10-2.5}$ samples (predicted ± SD).*

Table 2. *Average source mass contributions to $PM_{10-2.5}$ at Ulaanbaatar*

Source	$PM_{10-2.5}$ mass µg m^{-3}
Soil 1	42.5 (3.0)[a]
Combustion	11.9 (0.7)
Soil 2	54.5 (4.0)
Road dust	13.9 (1.9)

[a] *Standard deviation*

the source location, with the Soil 2 source originating more locally in Ulaanbaatar where there is likely to be a greater concentration of settled combustion particles and coal dusts mixed into the crustal matter, hence the higher presence of BC in the source profile. Analysis shows that the two soil sources are correlated (r^2 = 0.8). However, a three factor PMF solution which essentially combined the two crustal matter sources yields unsatisfactory results, primarily due to a high Q value and significant skews in the residual plots (more highly positive or negative for a number of elements) particularly for Al, Si, K, Ca and Fe, the major contributing elements to crustal matter.

Interestingly, the third factor has been identified as a coal combustion source contribution for the coarse fraction and this contains the majority of black carbon and a significant sulphur component. The time–series plots of the per sample mass contributions presented in Figure 5 show that the $PM_{10-2.5}$ coal burning source contributions peaked during winter indicating that it was likely to be due to emissions from local coal combustion sources. While the emission of particles from combustion sources are primarily in the sub-micrometer range (Hedberg et al., 2002) there is likely to be some agglomeration, condensation or impaction of the fine fraction onto coarser particles (and/or onto the coarse filter of the SFU) to provide a measurable contribution to the coarse fraction sample. The fourth source has been identified as a local road dust component as this profile contains BC and most of the zinc along with elements typical of crustal matter. Mongolia is understood to have phased out the use of leaded petrol over the past few years (UNEP, 2008) and lead was only detected above the LOD (~100 ng m^{-3}) in a few of the coarse particulate matter samples. Further discussion is provided in Section 3.4.

Figure 5 shows the dominance of crustal matter source contributions to the coarse particle fraction at Ulaanbaatar with combined maximum concentrations up to 460 µg m^{-3}. Figure 6 shows that the crustal matter contributions are highest during spring and autumn with significant contributions during winter from the Soil 2 crustal matter source. The temporal variations in crustal matter contributions are consistent with precipitation patterns in Ulaanbaatar as most rain falls during summer and a consequent suppression of dust generation. Spring, autumn and winter in Mongolia are generally dry with spring and autumn the windiest seasons (Xuan et al., 2004).

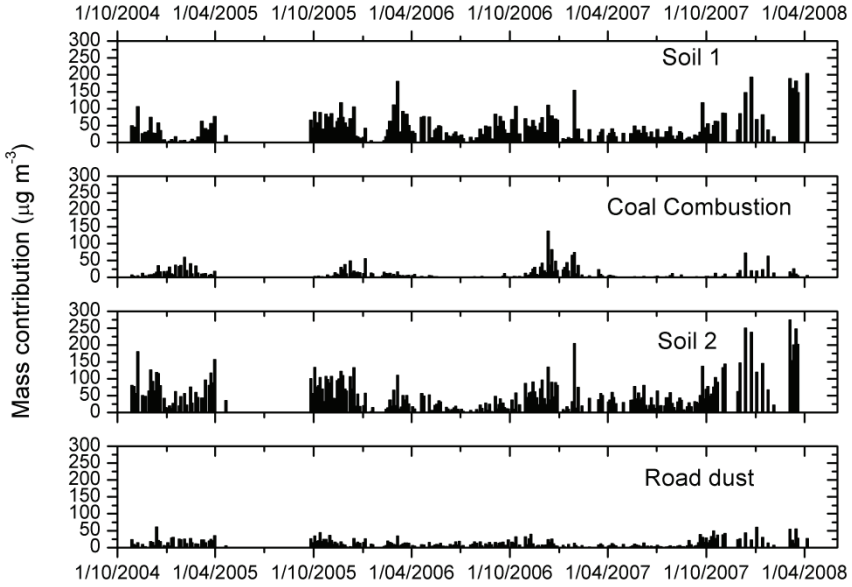

Figure 5. *Contribution time series of resolved sources for $PM_{10-2.5}$ at Ulaanbaatar.*

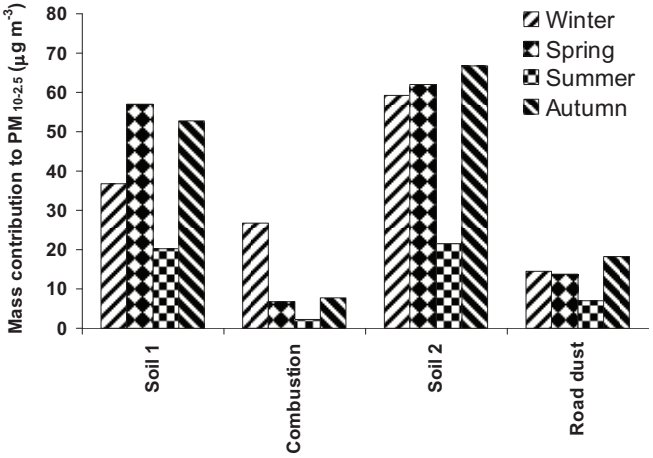

Figure 6. *Seasonal source mass contributions to $PM_{10-2.5}$ at Ulaanbaatar.*

3.3. $PM_{2.5}$ data analysis

A total of 232 fine particulate matter samples were included in the receptor modelling analyses of Ulaanbaatar data. While a total of 25 elemental constituents were detected above their respective LOD, 15 species were selected for PMF modelling ($PM_{2.5}$, BC, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Cu, and Zn) as other elements were only present in a few samples and/or the S/N ratio was low. Table 3 presents the mean, standard deviation, median, maximum, minimum, and number of samples above LOD and S/N ratio for individual species.

The source profiles for the $PM_{2.5}$ data were derived in the same way as for the $PM_{10-2.5}$ data. A seven-source model was found to offer the most appropriate solution after rotation (FPEAK = -0.6). Figure 7 shows the comparison between modelled (PMF) $PM_{2.5}$ and measured $PM_{2.5}$ concentrations (r^2 = 0.89). The average mass contributions of each of the sources to ambient fine particle concentrations are shown in Table 4 and the elemental source profiles are presented in Figure 8. The derived source profiles were compared to measured source profiles and/or those reported in other studies to ensure they made physical sense.

Table 3. *Summary statistics for $PM_{2.5}$ and elemental concentrations at Ulaanbaatar*

ng m^{-3}	Arithmetic Mean	StdDev	Median	Maximum	Minimum	LOD # Samples > LOD[a]		S/N
$PM_{2.5}$	46 000	51 000	28 000	400 000	6 000	-	-	-
BC	7 290	10 454	4 242	94 206	680	300	232	2.75
Na	290	425	112	2 642	0	500	88	0.13
Mg	326	276	235	2 083	31	80	200	0.62
Al	1 150	1 224	745	7 627	0	44	227	0.81
Si	2 305	1 740	1 871	10 554	129	33	232	17.20
P	79	106	42	773	0	62	157	0.24
S	1 969	3 978	900	40 079	125	31	232	17.55
Cl	139	133	88	849	12	28	232	2.14
K	324	239	243	1 558	35	22	232	7.00
Ca	789	559	652	3 194	50	19	236	11.92
Ti	37	33	28	156	0	15	191	0.27
Mn	15	14	11	65	0	11	178	0.18
Fe	523	388	416	2 150	26	10	232	0.62
Cu	10	29	3	373	0	13	105	0.21
Zn	44	54	30	400	0	14	213	0.55

[a] *Limit of detection*

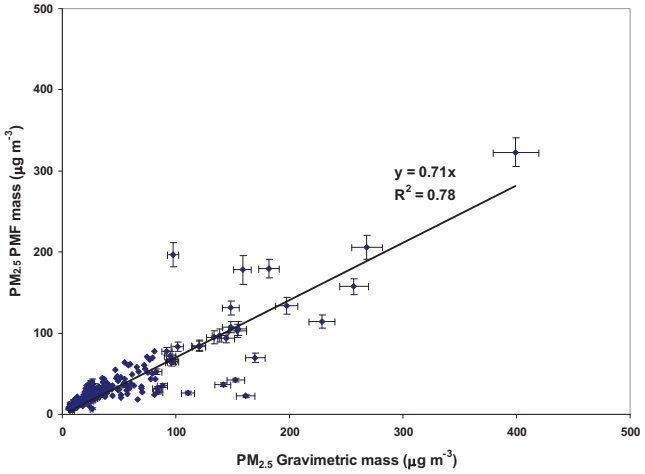

Figure 7. *Plot of predicted (PMF) $PM_{2.5}$ mass concentrations versus measured (gravimetric) $PM_{2.5}$ mass concentrations.*

Table 4. *Average source mass contributions to $PM_{2.5}$ at Ulaanbaatar*

Source	$PM_{2.5}$ mass µg m^{-3}
Soil	5.0 (0.4)[a]
Coal combustion 1	12.3 (0.8)
Coal combustion 2	11.6 (1.8)
Motor vehicles	1.9 (0.6)
Biomass burning	1.1 (0.2)
Road dust	3.0 (0.4)
Zinc	0.6 (0.3)

[a] *Standard deviation*

The first source profile was identified as the fine fraction of airborne soil originating from crustal matter as the profile contains the majority of Al and Si with an Si:Al ratio of approximately 2.5:1. The second factor, and highest source contributor, was identified as a coal burning source as it was dominated by black carbon with a significant sulphur component as found in other receptor modelling studies (Mukai et al., 1993; Mukai et al., 2001; Song et al., 2006). The third factor was also attributed to coal combustion sources but with a lesser sulphur component and some differences in minor elemental species present in the source profile composition. We suggest there are two distinct coal combustion source types present in the Ulaanbaatar airshed with differing combustion characteristics. Further discussion is provided in Section 3.4. The fourth source has been identified as originating from motor vehicles as a similar separation of elemental components associated with fine particle motor vehicle emissions has been reported elsewhere (Mizohata et al., 1995; Schauer et al., 2006; Wahlin et al., 2006). The fifth source represents biomass burning contributions to $PM_{2.5}$ ambient mass concentrations due to the association of black carbon and potassium in the profile. Wood burning for cooking is used all year in Ulaanbaatar but there was also evidence that forest fire events to the north of the region can contribute at certain times. The sixth factor has been attributed to finer fraction of airborne road dust and the seventh source extracted from the PMF analysis contained a distinct Zn component to the elemental signature. It would appear from the PSCF analysis that this originates to the west of Ulaanbaatar.

The temporal variations on source contributions to $PM_{2.5}$ are presented in Figure 9. Note that the scales for the coal combustion sources are an order of magnitude higher than the other plots.

The temporal variation in source contributions shows that coal combustion peaks during winter (December – February) in Ulaanbaatar. Seasonal contributions by $PM_{2.5}$ sources are presented in Figure 10. Peak contributions from the $PM_{2.5}$ crustal matter and road dust sources occurred during spring and autumn commensurate with driest seasons as did the biomass burning source.

3.4. Discussion

Crustal matter sources. The factor analysis of $PM_{10\text{-}2.5}$ and $PM_{2.5}$ fractions has shown that crustal matter sources are significant contributors to air particulate matter concentrations at Ulaanbaatar, primarily dominating the coarse fraction. We have identified two coarse fraction crustal matter elemental profiles (Soil 1 and Soil 2) and suggest that they originate from different source areas based on the BC content and other elements in the profile. The crustal matter elemental profiles derived by PMF were compared to actual soil samples collected in and around Ulaanbaatar (Markwitz et al., 2008). Markwitz et al. (2008) collected crustal matter samples from sand dunes, open countryside and urban locations (sample locations and descriptions are provided in the reference). The crustal matter samples were then compressed into discs and elemental concentrations determined by IBA at GNS. Due to the nature of the samples, BC was not measured in that study. Figure 11 presents elemental profiles (as the percentage of the total measured elemental mass) for elements common to the crustal matter samples collected by Markwitz et al. (2008) and those derived from the coarse and fine PMF analysis in this study.

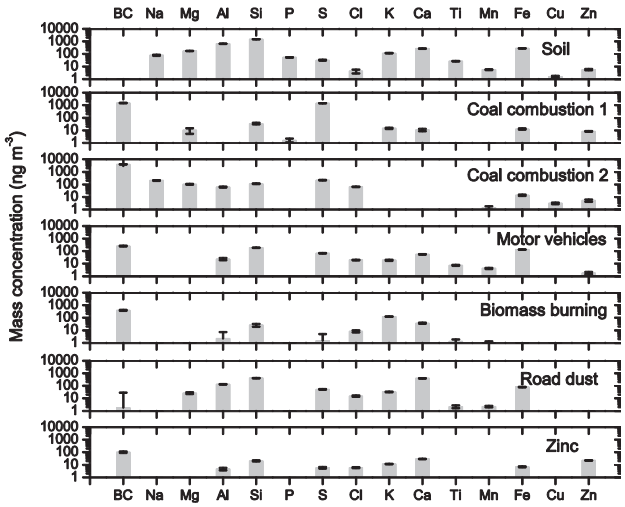

Figure 8. *Elemental source profiles derived by PMF for $PM_{2.5}$ samples (predicted ± SD).*

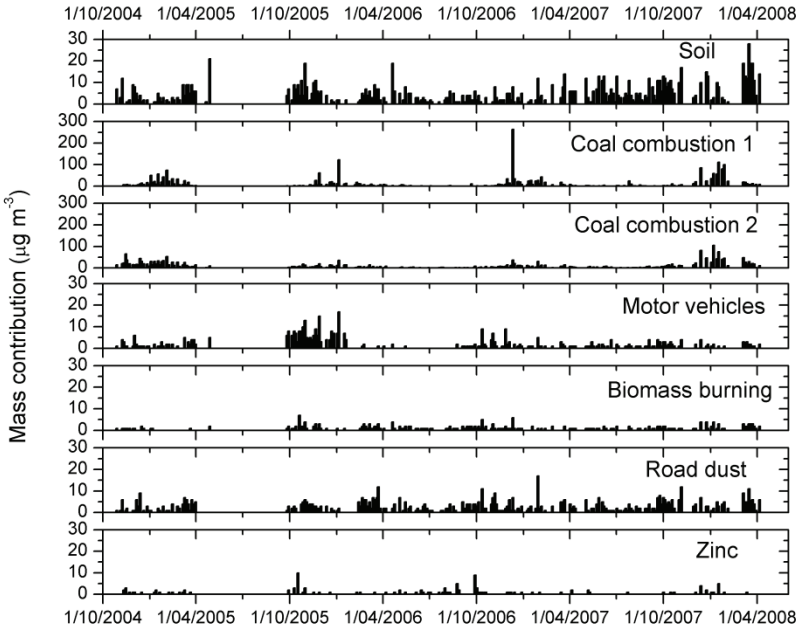

Figure 9. *Contribution time series of resolved sources for $PM_{2.5}$ at Ulaanbaatar (note the difference in scale for coal combustion sources).*

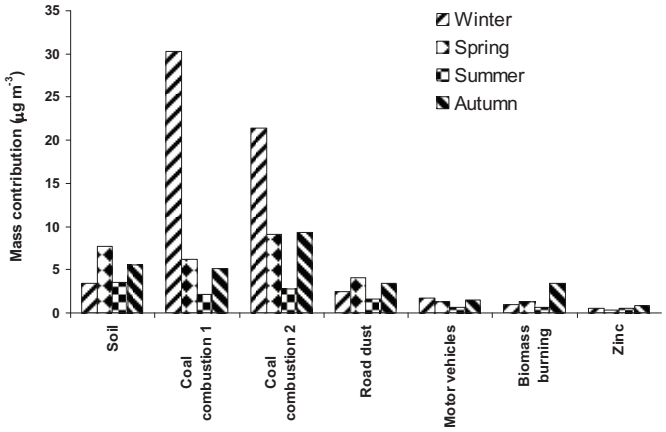

Figure 10. *Source contributions to $PM_{2.5}$ by season at Ulaanbaatar.*

Figure 11 shows that the sand samples have the highest Si:Al ratio and a lower iron and calcium content in accordance with the higher silica content of sand. The city and country crustal matter samples have a similar composition to each other. The air particulate matter crustal matter profiles derived by PMF all have a lower Si:Al ratio than the crustal matter source samples, most likely due to particle size fractionation of the minerals making up crustal matter with aluminosilicates present in the fine fractions. These results indicate that the Soil sources are largely derived from the transport of fine loess rather than sand as observed by Zhang et al. (2003).

Mass contributions to $PM_{10\text{-}2.5}$ from the Soil 1 component were generally higher than Soil 2 and probably represent dust source areas from the Ulaanbaatar, surrounding countryside environs and long-range transport. The Soil 2 dust source has been identified as more localised to the Ulaanbaatar urban area due to a significant BC component and the presence of P and Cu in the elemental soil source profile. Analyses of air mass back–trajectories using HYSPLIT (Draxler and Rolph, 2003) indicate a distinct westerly directional component for sample days where there was a significant Soil 2 contribution but little or no contribution from the Soil 1 source. West of the monitoring site, across Ulaanbaatar, are two large coal fired power stations as indicated in Figure 12. Associated with the power stations are large stockpiles of coal and slag dumps that are likely to be significant sources of fugitive dust emissions and may account for the BC observed in the Soil 2 elemental profile. Other urban source areas of fugitive dusts such as construction, excavations and land clearance, unsealed yards and roads are also likely to contribute to the mix.

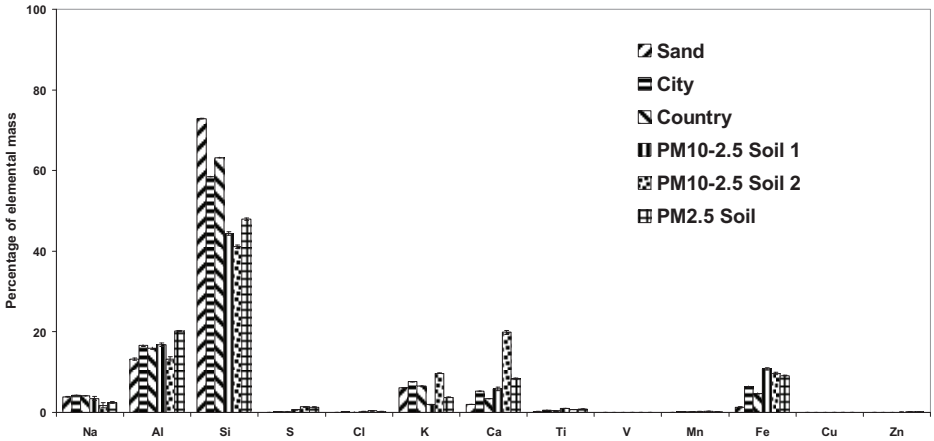

Figure 11. *Elemental profiles for crustal matter source samples and those derived for coarse and fine air particulate matter samples by PMF.*

Figure 12. *Aerial view of Ulaanbaatar indicating monitoring site location (★) and coal fired power stations to the west (source: Google maps 2008).*

Air–mass back trajectories for peak Soil 1 and Soil 2 source contributions indicate source areas to the west and north respectively. Northwest winds peak during spring in Mongolia due to the breakdown in the Siberian High Pressure zone after winter (Xuan et al., 2004). Xuan et al. (2004) found that the Asian Dust Storm events originate in the deserts of southern Mongolia/northern China. Other studies have shown source areas in western and northwestern China and trajectories across Mongolia from the northwest to southeast (see for example Zhang et al., 2003; Xuan et al., 2004; Song et al., 2006; Wang et al., 2006; Kim et al., 2007). One peak dust event in Ulaanbaatar as determined from the PMF analysis has been corroborated with satellite images and other observations in eastern Asia that indicate long-range transport mechanisms. For example, the Soil 1 source showed a peak concentration on 6 March 2006 (180 μg m^{-3}) and satellite imagery (NASA Earth Observatory) for 9 March 2006 shows the dust storm spreading out over eastern China as presented in Figure 13.

It seems evident from this study that significant loading of dusts were present in air–masses arriving at Ulaanbaatar from the west and northwest and that the crustal matter, particularly the $PM_{2.5}$ fraction (peak concentrations at Ulaanbaatar 20 – 30 μg m^{-3}) can be transported considerably further to the southeast and arrive at cities affected by Asian Dust Storm events such as Beijing (Zhang et al., 2005; Song et al., 2006). Figure 14 shows the PSCF analysis for the $PM_{2.5}$ soil source indicating potential source locations that include the deserts in the south of Mongolia (Gobi Desert), central Kazakhstan (Betpaqdala Desert) to the northwest of Ulaanbaatar, and possibly the Taklamakan Desert (Wang et al., 2008) in China to the west of Mongolia.

Combustion sources. Combustion sources were found to be significant source contributors to air particulate matter, primarily to $PM_{2.5}$, at Ulaanbaatar. Cold temperatures and inversion conditions during the winter severely limit the dispersion of air pollutant in Ulaanbaatar and therefore high concentrations of combustion derived $PM_{2.5}$ are recorded in the Ulaanbaatar airshed. In 2006/2007 approximately 4 900 000 tonnes of coal and 413 000 tonnes of wood were burnt in Ulaanbaatar (NAMHEM, 2007). Analysis of temporal variations in source contributions showed that coal combustion sources dominate during winter due the use of coal for heating and power generation. Air–mass back–trajectory analyses indicate that peak contributions from the Coal combustion 1 source occur during westerly winds possibly due to emissions from the coal fired power stations to the west (shown on the aerial photograph in Figure 12) directly impacting at the monitoring site. The Coal combustion 1 source profile is dominated by BC and S (most likely present as sulphate species) representative of high temperature coal combustion characteristic of power stations (Polissar et al., 2001). The Coal combustion 2 source represents emissions from coal fires used for domestic heating as a significant proportion of the urban population (120 000 households) in and around Ulaanbaatar live in Gers (48%) (traditional Mongolian house) or small brick dwellings (52%), both of which are heated by simple solid fuel appliances or open fires (NAMHEM, 2007). As such, the source profile is representative of low-temperature coal combustion with significant ash and crustal matter components (Na, Mg, Al, Si) (Zheng et al., 2005). Both coal combustion sources peak during winter due to demand for heating and the significant temperature inversion conditions effectively trapping pollutants in the Ulaanbaatar airshed. Source contributions to $PM_{2.5}$ from coal combustion during winter appear to be increasing annually. Some of the variation is probably due to interannual climate variations, however, a significant increase in the $PM_{2.5}$ coal combustion contributions over 2007/2008 winter period suggests that the increase may be due to coal usage. Figure 15 presents the average mass contributions to $PM_{2.5}$ from coal combustion sources for each winter (December–February) since monitoring began in 2004. Further monitoring is required to see if the trend continues.

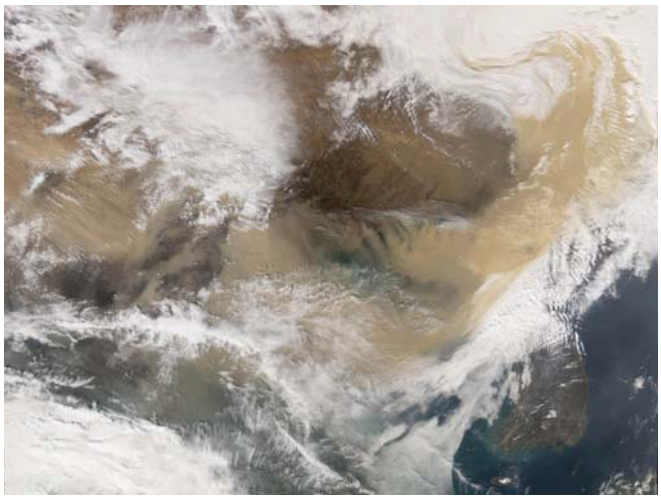

Figure 13. *Dust cloud (tan discolouration) spreading out over Eastern china and Korean Peninsula on 9 March 2006 (source: http://earthobservatory.nasa.gov/NaturalHazards).*

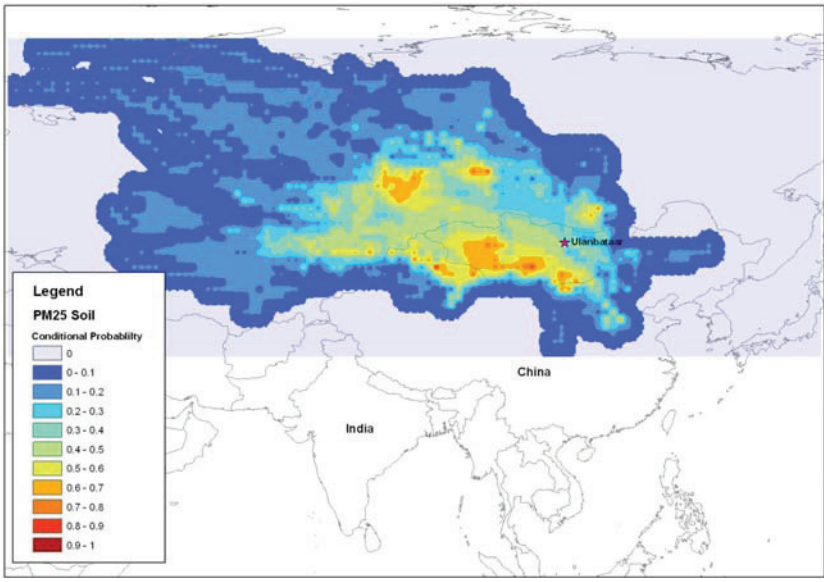

***Figure 14**. PSCF analysis for $PM_{2.5}$ soil source contributions showing potential source locations.*

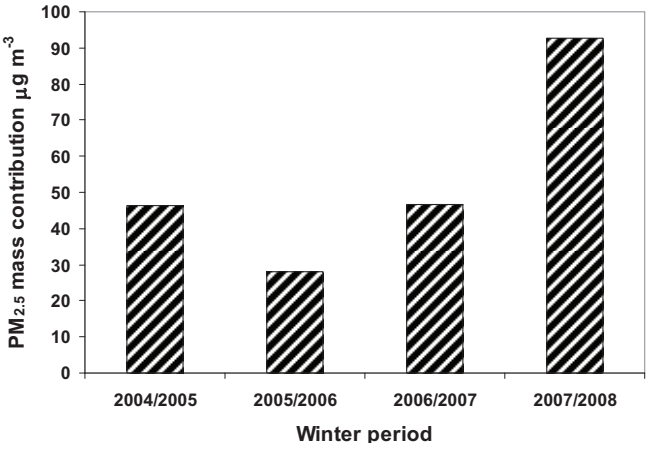

***Figure 15.** Average winter (December – February) contributions to $PM_{2.5}$ from coal combustion sources in Ulaanbaatar.*

The biomass burning source originates primarily from domestic cooking activities in Ulaanbaatar with peak contributions from forest fires to the north during spring and autumn. Forest fires are a common occurrence during the dry spring and autumn months in Mongolia (Nyamjav et al., 2007). Air–mass back–trajectory analysis for peak biomass burning events show that source emissions originate north of Ulaanbaatar. For example, a peak in biomass burning source contribution to $PM_{2.5}$ occurred on 20 April 2006 (4 µg m^{-3}). The back–trajectory presented in Figure 16 shows the air mass arriving at Ulaanbaatar from the north and satellite records show significant fires burning in southern Russia and northern Mongolia over the same period (Figure 17).

Figure 17 presents the satellite image for April 23, 2006, showing that large fires were burning in the foothills of the mountains that separate Russia (north) from Mongolia (south). The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite captured the image of the fires (actively burning areas outlined in red) and their accompanying large burn scars (dark brown). The smoke was blowing southeastward across Mongolia (from http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=16493).

The zinc source was found to be a minor contributor to $PM_{2.5}$ in Ulaanabaatar. Initially the association of zinc and BC in the profile suggested that it may be due to two stroke engine emissions (Begum et al., 2004). However, few vehicles in Ulaanbaatar are thought to be powered by two stroke engines and no other local zinc containing particulate matter emission source has been identified as yet. The PSCF analysis for the zinc source presented in Figure 18 indicates that the potential source area for the zinc source was northwestern China centred on Urumchi, the local provincial capital. The zinc source may be due to long–range transport of emissions from heavy industry in the area (e.g. zinc mining and smelting).

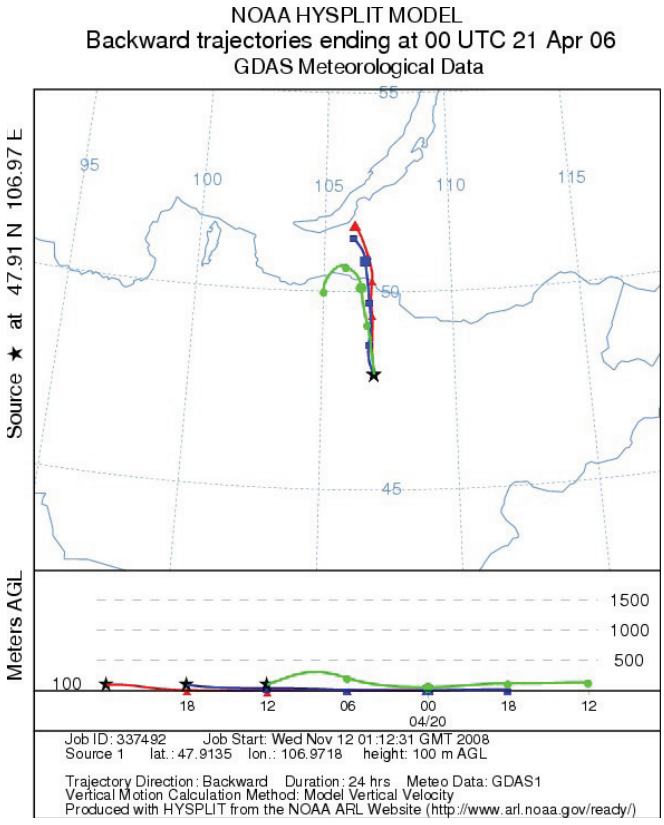

***Figure 16.** Air mass back-trajectory (24 hr) for April 20 2006 (Source: NOAA, HYSPLIT).*

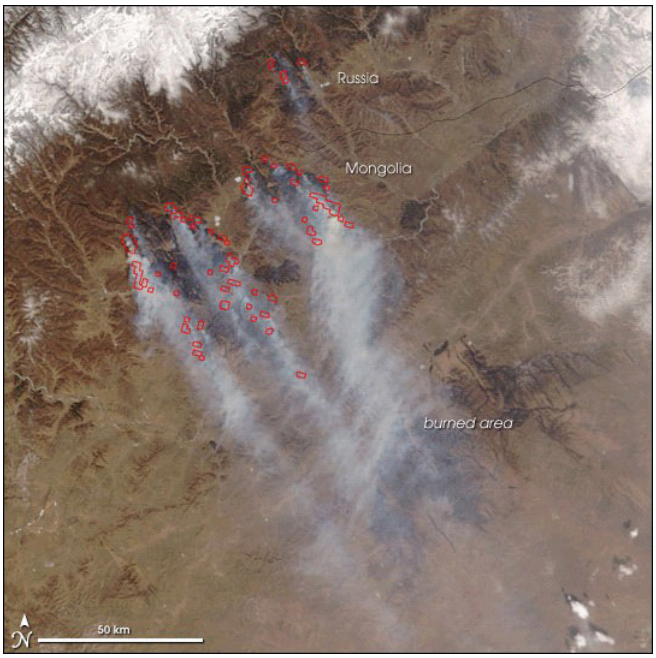

Figure 17. *Satellite image of forest fires burning in southern Russia and northern Mongolia on 23 April 2006 (source: NASA Earth Observatory at http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=16493).*

4. Conclusions

This study presented the results of four years of $PM_{10-2.5}$ and $PM_{2.5}$ monitoring data collected at Ulaanbaatar, Mongolia. Particulate matter concentrations were found to be extremely high at times with maximum PM_{10} concentrations measured at 1 100 µg m^{-3} and many days where concentrations were above 300 µg m^{-3}. The coarse particle fraction generally dominated PM_{10} but high $PM_{2.5}$ values were recorded during winter months with $PM_{2.5}$ values often over 100 µg m^{-3}. With such high particulate matter concentrations present in the Ulaanbaatar urban area there are likely to be significant health implications for the exposed population. Elemental concentrations within particulate matter collected onto filters were determined by IBA and factor analysis performed using Positive Matrix Factorisation.

Four source contributors were identified for the coarse particle fraction and seven sources derived for the fine particle fraction. Major sources contributing to particle concentrations were found to be crustal matter (primarily the coarse fraction) and coal combustion sources dominated the fine fraction during winter. Crustal matter sources were found to be generated both locally (urban dust sources) and transported to Ulaanbaatar from the west and northwest, particularly during the dry and windy months of spring and autumn. Dust storm events in this region are well known to generate the Asian Dust events that affect many parts of eastern and southeastern Asia during spring and can be transported out over the Pacific.

Source contributions to $PM_{2.5}$ were dominated by emissions from coal combustion sources with two distinct source types, the first identified as a high–temperature combustion source originating from power station emissions in the western part of Ulaanbaatar and the other from coal combustion used for domestic heating during winter. The monitoring data suggests that mass contributions from coal combustion sources are increasing. It was also found that, at times, forest fires in northern Mongolia and southern Russia can impact on air quality in Ulaanbaatar and a long–range trace source of zinc containing $PM_{2.5}$ particles was identified as originating in northwestern China.

Acknowledgements

This project was supported in part by the International Atomic Energy Agency through the Regional Cooperation Agreement Programme “RAS/7/015 - Characterization and Source Identification of Particulate Air Pollution in the Asia Region”.

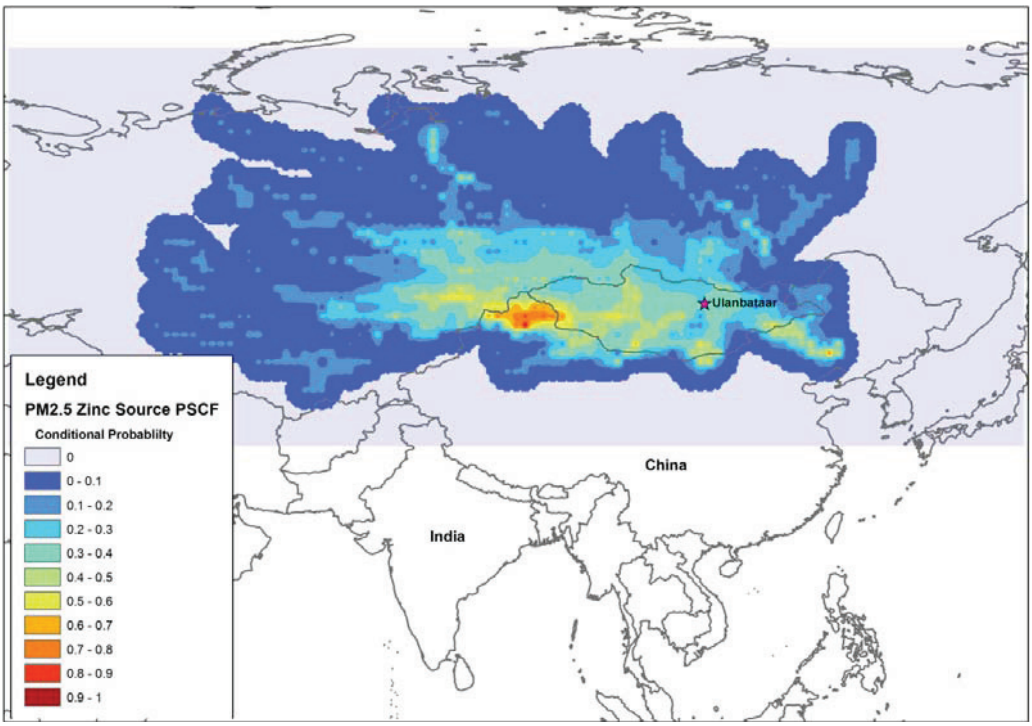

Figure 18. *PSCF analysis for the $PM_{2.5}$ zinc source showing a potential source location in northwestern China (Urumchi) to the west of Mongolia.*

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