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Discussions

Elements in PM$_{2.5}$
particles during the
Göte-2005 campaign

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Elemental content of PM$_{2.5}$ aerosol particles collected in Göteborg during the Göte-2005 campaign in February 2005

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Abstract

Göte–2005 was a measurement campaign in the city of Göteborg with the aim of studying the influence of the winter thermal inversions on urban air pollution. Elemental speciation of PM$_{2.5}$ aerosol particles, collected on Teflon filters at three urban sites and

5 one rural site in the Göteborg region, was a major part of the study. Trace element analysis was done by Energy Dispersive X-Ray Fluorescence (EDXRF) spectrometry and the concentrations of S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Br and Pb were determined. The elemental content of the particles in combination with information of local wind speed and direction and also backward trajectories were used to estimate

10 the source areas of the pollutants. We can conclude that S, V, Ni, Br, and Pb have their main sources outside the Göteborg area, since we cannot see elevated concentrations of these elements during an inversion episode. Sea traffic and harbour activities were also identified, primarily by the S and V content of the particles. This study proves that the elemental analysis by EDXRF presents valuable information for tracing the origin

15 of air masses arriving at a measurement site.

1 Introduction

Air pollution in urban environments is a major problem to human health. This has forced governments to invoke regulations controlling the pollution in an effort to protect their citizens. The control is achieved through the provision of air quality standards

20 that address the concentrations of the criteria pollutants above which harm may occur to human health. Particulate matter is one of these criteria pollutants which attracts increasing attention, since the environmental quality standards for particulate matter stipulated for the European Union (European Union, 1999) are hard to follow in many large cities (Baldasano et al., 2003). This is for example the case for Göteborg, Swe-

25 den, where the measurement campaign presented here was carried out in February 2005. The air quality standard, derived from the regulations in chapter 5 in the Swedish

environmental code based on the EU directive 1996/62/EC and its daughter directives, deals with particles having an aerodynamic diameter below $10\,\mu m$, PM_{10}. The standard stipulates the average annual concentration to be below $40\,\mu g\,m^{-3}$ with a 24 h limit value of $50\,\mu g\,m^{-3}$. This annual threshold is expected to be reduced to $20\,\mu g\,m^{-3}$

5 by the year 2010. The use of PM_{10} as an integrative measure of particle concentration is under discussion and new norms based on particles smaller than $2.5\,\mu m$, $PM_{2.5}$ are impending (European Union, 1999). The shift in concern is motivated by the higher anthropogenic input of $PM_{2.5}$, their ability to be transported over longer distances and thus influence a larger part of the population. The atmospheric wind system's ability

10 to transport $PM_{2.5}$ over long distances not only affects the exposure, but together with an analysis of the elemental content of the particles it helps in source apportionment studies. The World Health Organization (WHO) has recently updated their air quality guidelines to now focus on $PM_{2.5}$, a decision that is based on scientific evidence of the particles' adverse effect on health (WHO, 2005). There are several examples of

15 poor health that are associated with particulate matter even at levels close to the background concentrations found in most parts of the United States and Europe (Dockery et al., 1993; Pope and Dockery, 2006; Schlesinger et al., 2006). The integrative parameter for particulate matter mass, PM_{10} or $PM_{2.5}$, is not easy to use for source apportionment. Consequently, a more detailed knowledge of the constituents of the particles

20 is of great value (Ariola et al., 2004, 2006; Chow and Watson, 2002; Molnár et al., 2006). The measurements of the current study were a part of the larger air pollution measurement campaign Göte–2005 conducted in Göteborg, Sweden. The focus of the measurements presented here was to study the trace element content of $PM_{2.5}$ particles in Göteborg, the influence of temperature inversions and possible sources for the

25 trace elements in the particles to elucidate the difference between air masses arriving at the measurement site.

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2 Method

The measurements were conducted in Göteborg (57.69° N; 11.98° E, 500 000 inhabitants) on the Swedish west coast in February 2005 as part of the air pollution measurement campaign Göte–2005. The overall aim of the Göte–2005 measurement campaign was to study the influence of wintertime temperature inversions on the air pollution situation in Göteborg. February is normally a cold winter month in Göteborg and in 2005 the temperature varied between −9.1°C and +7.3°C with an average temperature of −0.6°C. Part of the measurement period was windy as several low pressure systems passed Göteborg. 40% of the time the wind was coming from north east or north north east, Fig. 1. The average wind speed ($m\,s^{-1}$) and wind direction (degrees) for the measurement period are calculated from noon each day and the day indicated in the figure is the same date as when the filters were collected. $PM_{2.5}$ particles were collected at three sites, Femman, Campus and Lipstick (Fig. 2), representing different urban conditions, and at one rural site, Råö. All sampling sites were located in places without point sources in the near vicinity.

The Femman site was on the roof of a commercial complex located approximately on sea level in the busy centre of Göteborg. The site is the main monitoring station for air quality maintained by the local environmental office in Göteborg and said to represent urban background. The sampler was positioned approximately 30 m above ground. Aerosol samples were collected between 4 February and 3 March 2005 at this site. The Chalmers Campus area is situated 2 km south of the city centre approximately 40 m above sea level. The area represents a less busy area which is traversed by 8000 vehicles per day as a yearly average. The Campus sampling site is located approximately 10 m above ground and 20 m from the street. Aerosol sampling was done between 7 and 28 February 2005. The Lipstick building is located on sea level 500 m north north east of the Femman site, in the docklands in the central parts of Göteborg. The sampling site was at the roof top level of the building 88 m above ground level. This site was selected with the expectation that it would be above low inversion

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layers. Aerosol samples were collected between 17 and 26 February 2005 at the site. The rural sampling site was at Råö which is located 35 km south of Göteborg. It was close to the sea, a few meters above sea level. The sampler had its inlet approximately 1.5 m above ground and aerosol samples were collected between 11 and 26 February.

5   Particle collection was done on 25 mm diameter Teflon filters with a pore size of 3 μm (PALL Teflo^{TM} R2PI025) using plastic cyclones (Casella Ltd, UK). The flow through the cyclone was kept constant by a critical orifice to maintain a particle cut off diameter of 2.5 μm. Samples were changed at noon on a daily basis, except at Råö where samples were changed with an interval of four to seven days due to the expected low concen-

10 trations at this site. All dates given in the tables are the date of filter collection, i.e. after sampling the particles. The meteorological information during the measurement campaign period was obtained from the local environmental office in Göteborg.

All obtained samples were analyzed for their elemental content by Energy Dispersive X-Ray Fluorescence (EDXRF) spectrometry (Van Grieken and Markowicz, 1993).

15 The spectrometer is based on three-axial geometry with a Mo secondary target that facilitates a good signal to background ratio that gives low detection limits, Table 1. The spectrometer was operated at 55 kV and 25 mA and the samples were analyzed for 1000 s (Boman et al., 2005; Gatari et al., 2006). For calibration of the spectrometer thin film standards having a certified uncertainty in the elemental concentration of

20 5% were used (Micromatter Inc., Seattle, WA, USA). By repeatedly analysing selected aerosol filter samples the mean analytical precision of the spectrometer has been determined to be 5% (Molnár et al., 2006). Spectral evaluation was done with the AXIL program (Bernasconi et al., 2000).

A Dionex Ion Chromatograph was used to analyse the SO$_4^{2-}$ content (Janhäll et al.,

25 2003) in the samples collected at the three urban sites between 17 and 26 February. The analysis was done using an analytical column IONPAC A59-SC, eluent 1.8 mM Na$_2$CO$_3$/1.7 mM NaHCO$_3$ with an eluent flow of 2 ml m^{-1} and conductivity detection.

For the gravimetrical determination of particle mass on the filters a Mettler Toledo

MT5 micro balance was used.

3 Results and discussion

The concentrations of S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Br, and Pb were evaluated and their average and median concentrations and uncertainties at the four mea-
5 surement sites are shown in Table 2. The results showed that S, Cl, K, Ca and Fe dominated in the sampled atmospheric aerosol particles. The Femman site had the highest concentrations of these elements except for Ca where the highest concentration was registered at the rural site in Råö. The uncertainty in Table 2 includes induced variations by meteorological conditions, sampling variations and analytical uncertain-
10 ties in the EDXRF evaluation of the elements. $PM_{2.5}$ mass concentrations in μg m^{-3} are also included in Table 2. Concentrations below detection limit (DL) have been replaced by DL/2 (Hornung and Reed, 1990) and the elements where more than half of the samples had concentrations below detection limits were denoted by <DL. The elemental, $PM_{2.5}$ and SO_4^{2-} concentrations from samples for the period 17 to 26 February
15 2005 are presented in Table 3 to facilitate comparison between the measurement sites in the city. The Teflon filters used in the measurement campaign were optimized for EDXRF analysis, thus the SO_4^{2-} determination using ion chromatography have higher uncertainty, assessed to be 15%.

For most of the elements in Table 2 the difference between their average concentra-
20 tions from the four sampling sites was small and within a factor of two. However, the daily concentrations of different elements were highly variable and this was mainly due to different weather conditions, as indicated by the high uncertainties in Tables 2 and 3 and the varying concentrations of sulphur at the Femman measurement site illustrated in Fig. 3. The median concentrations, see Tables 2 and 3, were in general less than
25 the average revealing a right skewed distribution of the elemental concentration in the sampled particles.

The influence from Eastern Europe was confirmed by the back trajectories (Draxler

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and Rolph, 2003) on 6 to 9 February together with the high S and Pb concentrations in the particles these days. Sulphur originating from combustion of S rich coal in Eastern Europe was more than two times higher than average and Pb from leaded gasoline, phased out only recently in this part of Europe (UNEP, 2006) was more than three
5 times higher than the average concentration. Janhäll et al., 2003 did measurements at different heights on the Gustavii Cathedral in the centre of Göteborg in 1999 to investigate the vertical distribution of different air pollutants. Although Total Suspended Particles (TSP) were measured, not $PM_{2.5}$, the concentrations of S and Pb were only slightly higher than the ones measured in this study, adding to the conclusion that these
10 elements are contained mainly in $PM_{2.5}$ and thus can be transported long distances.

    Implications of emissions from sea traffic and harbour activities were found on 4 and 5 February. These days the S concentrations were high, reaching $2600\,\mathrm{ng\,m^{-3}}$ and $1900\,\mathrm{ng\,m^{-3}}$ at Femman and Campus respectively, and the back trajectories indicated that the air masses passed over the North Sea, UK, and Denmark. The high S con-
15 centration might have originated from ship emissions, both in the vicinity of Göteborg and the North Sea. Göteborg hosts the largest port in the Nordic countries and the international sea traffic is allowed to use fuels with high S content. Compared to the median concentrations for the whole measurement campaign the V and Ni concentrations were also high, 8.9 and $6.8\,\mathrm{ng\,m^{-3}}$ for V and 3.8 and $2.4\,\mathrm{ng\,m^{-3}}$ for Ni at Femman
20 and Campus respectively, pointing further to ship emissions as suggested in previous studies (Molnár et al., 2006). Cooper and Gustafsson (2004) calculated the emissions of trace elements in Göteborg from ships with more than 100 Gross Register Tonnage using fuel bought in Sweden. Using the calculated elemental emissions as a sign of emissions from sea traffic and harbour activities it can be seen that when comparing
25 elements measured at Femman and Campus there was only a fraction of most elemental concentrations that were likely to come from sea traffic even during the days the air masses passed over the harbour and the North sea area.

    The concentrations of most of the elements had a different variation pattern at the high Lipstick site when compared to the Femman and Campus sites. Principal compo-

nent analysis (PCA) on concentrations obtained over the period from 17 to 26 February at the three city sites confirmed this phenomenon. The first and most influencing component of the PCA exhibited almost the same elemental loadings on data from Femman and Campus sites, but the same variance dependency can not be seen at the Lipstick site, Table 4.

While the elemental concentrations at Femman and Campus more than doubled on 23 and 24 February compared to those on 20 and 21 February, the concentration at the Lipstick site did not change to the same extent, Table 5. Twenty-third and 24 February were characterized by high wind speeds, between 6 and 11 m s^{-1}, compared to 1–6 m s^{-1} for the rest of the period 17 to 26 February. Although the local wind direction was determined to be more or less stable with winds coming from north east between the 20 and 26 of February, 72 h back trajectories showed that the air masses were coming from different areas on different days, suggesting different source regions as illustrated in Fig. 3. The air masses arriving to Göteborg during 20 and 21 February were coming from the northern part of the Atlantic Ocean, the North Sea and Scandinavia. The following day there was a rapid change in direction and now air was arriving from southern and middle Finland. On the 23 and 24 February the air masses were coming from the central Russia region. As the wind speed thereafter decreased more of the air originated from the Baltic countries before coming from the northern part of Norway and Sweden on 26 February. The trace element concentration data showed a general increase of many of the elemental concentrations on 23 and 24 February when compared to 20 and 21 February as depicted by Fe and S in Fig. 3. Trace element analysis is a effective tool for confirming the trajectory analysis of air mass origin.

Despite the fact that the airborne particles were being collected over several days, the same trend of increasing elemental concentrations was seen in the data from Råö when samples collected between 14 and 21 February and the ones for 21 to 25 February were compared. An explanation is that there are more coarse particles in the air during the windy period and as a result more of them join the PM$_{2.5}$ fraction. This phenomenon was shown in an investigation on effects of wind speed on the relation

between particles of different sizes by Kim et al. (2005). In comparison to the monthly average concentration of $20.5\,\mu\mathrm{g\,m^{-3}}$ recorded by the local environmental office, relatively high PM_{10}concentrations that ranged between 21.5 and $33.6\,\mu\mathrm{g\,m^{-3}}$ were reported on the same days in February. The particle cut off diameter of the cyclone is
5   not sharp and the lower diameters of the coarse mode particles are collected in the fine fraction. This gives higher concentrations of the typical coarse fraction elements like Cl, K, Ca, and Ti in $PM_{2.5}$. The higher concentrations of S, V, and Ni on 23 and 24 February were likely to originate from combustion processes in the eastern part of Europe where the air masses passed before reaching Göteborg. These elements are
10   normally found in the fine particle fraction and can thus be transported long distances before the settling of the particles. The good correlation between the S concentrations obtained from the EDXRF analysis with the sulphate concentrations from the IC analysis (r^2=0.96) shows that most of the measured particulate S was in the form of sulphate.
15   The higher Pb concentration is likely to come from particles originating from Eastern Europe. Although unleaded gasoline is used in all countries in the region (UNEP, 2006) lead is still dispersed in particles that are re-suspended by strong winds and traffic. Pb is also dispersed from the tail pipe systems of cars that previously used leaded fuel. Cl is the only element with stable concentration during the days between 20 and 24
20   February, Table 5, indicating little influence from sea salt and this agreed well with the wind direction over the period.

    On the night between the 27 and 28 of February a strong night inversion was identified. Despite the 24 h sampling period, covering more than the inversion episode, the increase in concentration for most elements was approximately a factor of two when
25   compared to the median concentration for the whole measurement campaign period, with the exception of Cl and Fe. The Fe concentrations were the highest recorded during the measurement campaign, $350\,\mathrm{ng\,m^{-3}}$ at Femman and $230\,\mathrm{ng\,m^{-3}}$ at the Campus site. The Cl concentrations were the second highest with concentrations of $2400\,\mathrm{ng\,m^{-3}}$ and $1500\,\mathrm{ng\,m^{-3}}$ at Femman and Campus, respectively. The local en-

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vironmental office had their highest record of PM$_{10}$ at the same time with an hourly maximum of 177.2 μg m^{-3} on 27 February at 11:00 p.m., a very high value when compared to the monthly average of 20.5 μg m^{-3}. This type of night and early morning inversion episodes is known to lead to higher concentrations of especially traffic re-
5 lated elements like K, Cu, Zn and Pb (Janhall et al., 2006), but this was not evident from these 24 h measurements, probably because the inversion layer was broken before morning rush hours. During this night the simulated 1 h mixing heights were very low for six hours from midnight, giving further evidence of the inversion episode.

The highest Cl concentrations were recorded on 10 February when the wind was
10 coming from the North Sea area in the south west direction from Göteborg with a wind speed of approximately 6 m s^{-1}. The Cl concentration indicated the influence of sea salt particles. Comparing the sea salt ratio between S and Cl (Jaenicke and Schutz, 1988) with the ratio in the sample from 10 February shows an increase in S that could indicate emissions from sea traffic.
15 The elemental ratios between the median concentrations at Campus and Råö show a slight increase (<50%) or no increase at all at the Campus site of elements normally connected to urban activities like traffic and industries (V, Fe, Ni, Cu, Zn, Pb). This, together with the fact that the Pb concentrations were below the annual national environmental quality standard limit value for Pb in ambient air, 0.5 μg m^{-3}, in all samples
20 indicates that the urban air in Göteborg is comparatively clean when trace elements are considered.

The current study confirms some source apportionments from earlier studies in Göteborg. A measurement made by Moloi et al. (2002) in March 2000 on the same campus area as in this campaign shows the same range of concentrations of trace
25 elements. The averages of the S concentrations differed almost 50% between the two Campus measurements with the highest S concentration in the current study. Pb was found in the particles in 2000, but the Pb concentration was below the detection limit in this study, indicating a general decrease of Pb in the particles due to the use of unleaded gasoline. Factor analysis by Moloi et al. (2002) showed that most of the

collected PM$_{2.5}$ particles came from sea spray and industrial activities in the harbour area, indicated by Cl, Ni, and Br. The influence of vehicle emissions was also seen from the content of K, Cu, Zn and Pb. In this Göte-2005 study principal component analysis of the samples collected on Campus during 17 to 26 February showed that V, Ni and Br formed one component that can be a sign of influence from the sea traffic and the harbour area together with long distance transported aerosols, as suggested by Moloi et al. (2002). Since Cl that is known to be a signature element of sea salt, is in a component of its own. The V, Ni and Br concentrations might instead indicate the influence of combustion of heavy fossil fuels, both from sea traffic and from the Eastern Europe region, since the wind direction during this period was dominated by wind from north east, with westerly wind in the beginning of the period. In an European Community Respiratory Health Survey (ECRHS) Götschi et al. (2005) measured the elemental content of PM$_{2.5}$ for one year including March 2000 in 21 locations in Europe and Göteborg was one of them. The reported concentrations were very similar to those measured in Stockholm and Uppsala in the same study, the ones obtained by Moloi et al. (2002) and in this study. Götschi et al. (2005) observed a difference of up to 80 times for some elements between the European locations used in that study. The results included large seasonal and daily variations in elemental concentrations rendering difficulties in their epidemiological assessment of the fine particle influence on human health. The high daily variation was also seen in the present study, making this detailed analysis and interpretation of the results necessary in order to better understand the influences of possible sources on the elemental concentrations in urban aerosol particles.

4 Summary and conclusions

During the measurement campaign one night-time temperature inversion was recognised as well as some other days with exceptional elemental concentrations. Since the concentrations of S, V, Ni, Br, and Pb did not increase during the inversion their

major sources had to be seen as of non local origin. Back trajectory studies pointed to Eastern Europe as a major source area for S, Fe, Zn, and Pb. In this detailed study the main parameters influencing the elemental content of the $PM_{2.5}$ particles that were collected was found to be wind speed and wind direction. These parameters had to be complemented by back trajectory studies, since the areas over which the air mass has been passing play a major role in the composition of the $PM_{2.5}$ particles. In this way differences in elemental composition, for different number of elements, can be used to identify the influence of different source areas. Pinpointing more explicit sources is not possible since the air is mixed during long distance transport and long measurement times leading to the conclusion that shorter measurement periods are needed as well as better knowledge of emission from different sources. From the detailed analysis of the elemental composition it can be concluded that S is a suitable tracer for air masses coming both from Eastern Europe and from the sea. High concentrations of V and Ni indicate influence from sea traffic and the harbour area as well as Eastern Europe. A comparison between the elemental ratios of sea salt elements and the same elements in the analysed particles makes it possible to estimate that 75% of the measured S does not come from sea salt, but from other sources most likely to be sea traffic in the same sea. The inversion period helped us conclude that Pb and S are not emitted in the Göteborg area that was covered by the inversion.

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Table 1. Detection limits (DL) in ng m^{-3} for the analysed elements.

Element	DL
S	40
Cl	15
K	3.8
Ca	2.3
Ti	1.3
V	1.0
Mn	0.56
Fe	0.44
Ni	0.43
Cu	0.38
Zn	0.33
Br	0.23
Pb	0.29

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Table 2. Average, uncertainties (Uncert) and median concentrations in ngm^{-3} for the analysed elements and the PM$_{2.5}$ mass concentrations at the four sites. N=is the number of filters with elemental concentration above the detection limit. Maximum number of filters at Femman were 29 sampled between 4th February and 3rd March 2005, 26 at Campus for the period 7th to 28th February, 17 at the Lipstick site for the period 17th to 26th February and 4 at Råö between 11th and 26th February. PM$_{2.5}$ concentration is given in μg m^{-3}. Concentrations below detection limit (DL) have been replaced by DL/2. <DL indicates that more than half of the samples have concentrations below DL.

	Femman				Campus				Lipstick				Råö			
	Average	±	Uncert	Median	N=	Average	±	Uncert	Median	N=	Average	±	Uncert	Median	N=	Average	±	Uncert	Median	N=
S	1400	±	1100	900	29	1300	±	920	1200	26	630	±	380	490	10	1200	±	690	970	4
Cl	580	±	620	320	29	520	±	560	320	26	430	±	290	310	10	120	±	180	65	4
K	150	±	94	130	28	120	±	72	100	24	82	±	36	82	9	120	±	100	71	4
Ca	46	±	30	45	27	47	±	32	47	25	49	±	35	39	10	50	±	44	32	4
Ti	3.1	±	3.5	<DL	11	3.9	±	6.8	<DL	9	2.2	±	3.3	<DL	2	3.1	±	2.6	1.8	3
V	2.5	±	3	<DL	12	1.5	±	2.1	<DL	6	0.72	±	0.71	<DL	1	3.5	±	4.1	1.7	4
Mn	2.9	±	2	3.4	21	2.3	±	2.2	2.1	15	1.6	±	1.6	<DL	5	2.1	±	1.5	1.6	3
Fe	100	±	77	85	29	82	±	61	62	26	82	±	56	66	10	60	±	46	48	4
Ni	5.6	±	8.9	2.7	25	3.1	±	3.5	2.1	23	3	±	2.6	2.1	9	2.7	±	3.2	1.4	3
Cu	3.6	±	2.6	3.4	27	2.9	±	1.7	2.4	25	3.1	±	1.9	2.7	10	3.6	±	4.5	1.8	4
Zn	31	±	26	23	29	27	±	29	15	26	16	±	7.9	14	10	24	±	19	17	4
Br	2.8	±	2.2	2.1	26	2.2	±	1.7	2.1	25	3.3	±	1	3.1	10	3.6	±	4.9	1.7	4
Pb	6.2	±	9.5	<DL	11	5.3	±	7.8	<DL	10	2.6	±	3.9	<DL	3	5.7	±	5.5	3	2
PM$_{2.5}$	14	±	12	9.9	27	12	±	9	9	26	6.5	±	3	6.5	10	6.9	±	3.5	6.1	4

Table 3. Average, uncertainties (Uncert) and median concentrations in ng m^{-3} for the analysed elements, SO$_4^{2-}$ and the PM$_{2.5}$ mass concentrations at the three city sites. N=is the number of filters with elemental concentration above the detection limit. Only the period when samples were collected simultaneously at the three sites are shown (17–26 February). SO$_4^{2-}$ and PM$_{2.5}$ mass concentration is given in μg m^{-3}. Concentrations below detection limit (DL) have been replaced by DL/2. <DL indicates that more than half of the samples have concentrations below DL.

		Femman				Campus				Lipstick			
	Average		Uncert	Median	N=	Average		Uncert	Median	N=	Average		Uncert	Median	N=
S	1200	±	790	1000	10	1200	±	920	950	10	630	±	380	490	10
Cl	500	±	410	310	10	390	±	180	320	10	430	±	290	310	10
K	120	±	41	110	10	83	±	55	86	8	82	±	36	82	9
Ca	46	±	30	39	10	48	±	43	49	9	49	±	35	39	10
Ti	3.8	±	4.2	<DL	4	5.9	±	10	<DL	3	2.2	±	3.3	<DL	2
V	1.9	±	2	<DL	4	0.93	±	1.4	<DL	1	0.72	±	0.71	<DL	1
Mn	2.7	±	2.2	3.4	7	2.2	±	2.7	<DL	4	1.6	±	1.6	<DL	5
Fe	110	±	68	110	10	83	±	71	62	10	82	±	56	66	10
Ni	5.5	±	6.2	3.4	9	3.8	±	3.7	2.7	29	3	±	2.6	2.1	9
Cu	3	±	1.6	3.1	9	3	±	1.8	2.7	9	3.1	±	1.9	2.7	10
Zn	25	±	19	20	10	22	±	21	14	10	16	±	7.9	14	10
Br	1.7	±	0.9	1.7	9	2	±	2.1	2.1	9	3.3	±	1	3.1	10
Pb	5.4	±	8.3	<DL	4	4.4	±	7.3	<DL	3	2.6	±	3.9	<DL	3
SO$_4^{2-}$	4.4	±	3.4	3.2	8	3.6	±	2.5	3.2	8	2.1	±	2.3	1.7	9
PM$_{2.5}$	9.2	±	5.1	9.3	29	8	±	4.3	7.9	26	6.5	±	3	6.5	10

Table 4. The three main components of the Principal Component Analysis of the elemental concentrations at the three city sites during 17th–26th of February. The results are Varimax rotated with Kaiser normalization. Elemental component contributions higher than 0.7 are indicate in bold. %Var is the percentage explained by the component.

| | Femman | | | Campus | | | Lipstick | | |
	Comp.1	Comp.2	Comp.3	Comp.1	Comp.2	Comp.3	Comp.1	Comp.2	Comp.3
S	**0.95**	0.16	0.04	**0.81**	0.49	−0.21	0.11	**0.90**	−0.19
Cl	−0.36	**0.71**	−0.37	−0.18	−0.13	**0.96**	**0.75**	−0.46	0.06
K	**0.89**	0.27	0.23	**0.71**	0.58	−0.18	0.57	0.45	0.26
Ca	**0.88**	0.42	−0.05	**0.87**	0.37	0.00	0.30	0.26	**0.72**
Ti	**0.94**	−0.01	0.21	**0.97**	−0.08	−0.11	**0.98**	0.12	0.06
V	0.53	0.59	−0.54	0.27	**0.90**	−0.03	−0.20	0.46	−0.22
Mn	0.64	0.57	0.35	**0.78**	0.47	−0.07	**0.74**	0.24	0.54
Fe	**0.83**	0.01	0.53	**0.85**	0.44	−0.20	**0.96**	0.25	−0.03
Ni	**0.84**	0.09	0.32	0.17	**0.92**	−0.19	−0.07	0.03	−0.07
Cu	0.27	0.10	**0.93**	**0.74**	0.39	0.40	**0.78**	−0.02	0.39
Zn	**0.95**	0.00	0.28	**0.83**	0.52	−0.13	0.38	**0.91**	0.06
Br	0.21	**0.84**	0.30	0.37	**0.92**	0.06	0.00	−0.22	**−0.85**
Rb	**0.97**	−0.01	−0.02	**0.94**	0.21	−0.11	0.01	**0.93**	−0.17
%Var.	58	17	16	51	32	10	32	26	14

Table 5. Average concentrations in $\mathrm{ng\,m^{-3}}$ for the analysed elements at the urban sites for 20th–21st and 23rd–24th February, respectively. <DL means below detection limit. PM$_{2.5}$ and PM$_{10}$ mass concentrations are given in $\mu\mathrm{g\,m^{-3}}$. PM$_{10}$ mass concentrations are from the local environmental office.

	Femman		Campus		Lipstick	
	20–21/2	23–24/2	20–21/2	23–24/2	20–21/2	23–24/2
S	390	2400	770	2700	820	970
Cl	310	290	290	300	280	280
K	75	180	88	170	82	110
Ca	16	92	31	120	39	53
Ti	<DL	10	<DL	23	<DL	6.2
V	<DL	4.1	<DL	4.8	<DL	<DL
Mn	<DL	5.1	<DL	6.5	1.4	4.1
Fe	68	210	62	210	66	100
Ni	2.7	15	5.8	7.5	2.1	3.4
Cu	4.1	3.8	1.7	5.5	2.4	3.4
Zn	13	57	14	59	16	23
As	<DL	8.9	2.7	7.9	<DL	6.8
Br	0.69	2.1	1.4	4.8	2.7	3.1
Pb	<DL	20	<DL	17	7.5	9.6
PM$_{2.5}$	3.1	17	5.8	14	6.1	9.7
PM$_{10}$	11	26	11	26	11	26
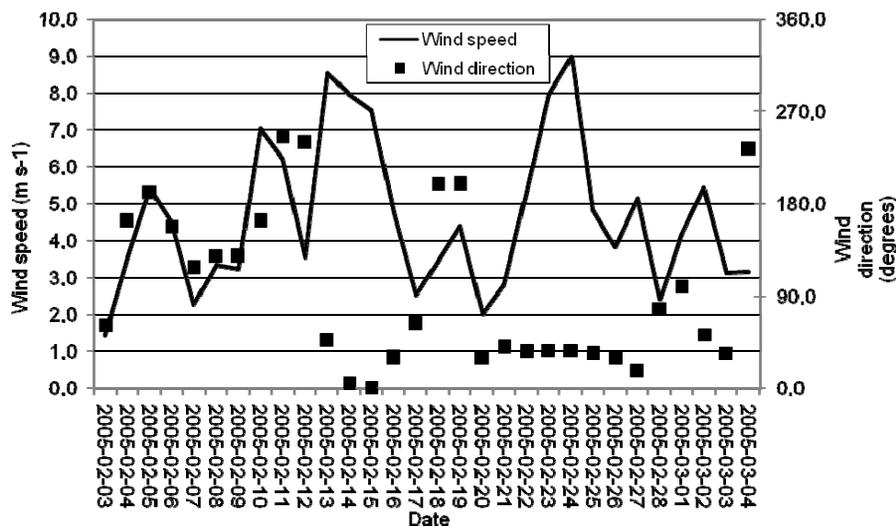
Fig. 1. The average wind speed (m s^{-1}) and wind direction (degrees) for the measurement period of this study. The averages are calculated from noon each day and the day indicated in the figure is the same date as when the filters were collected. 0 (and 360) degrees is wind coming from north, 90 degrees is east, 180 degrees south and 270 degrees is westerly winds.
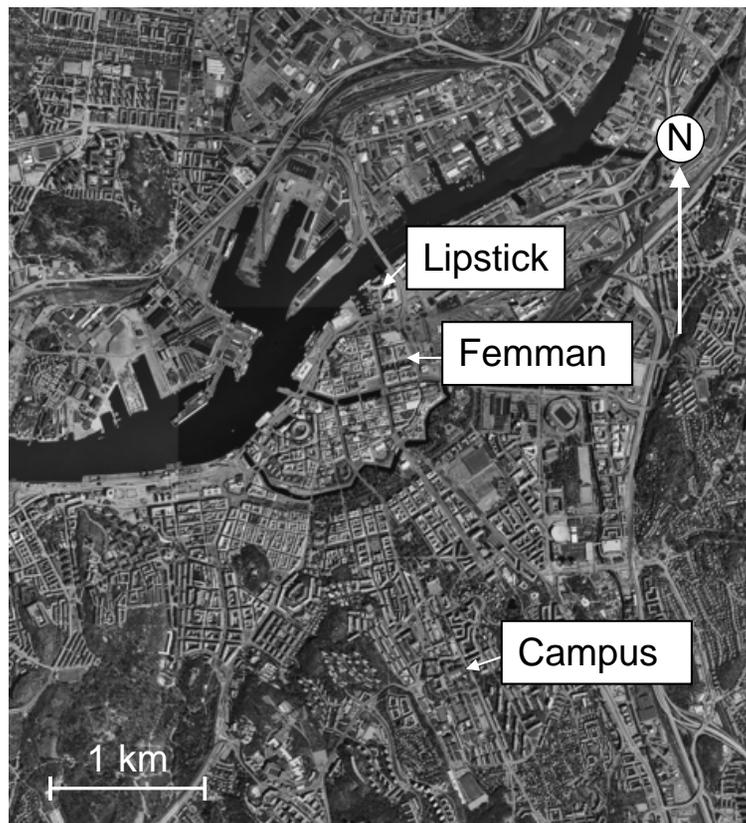
Fig. 2. Map showing the location of the urban measurement sites in Göteborg, Sweden.
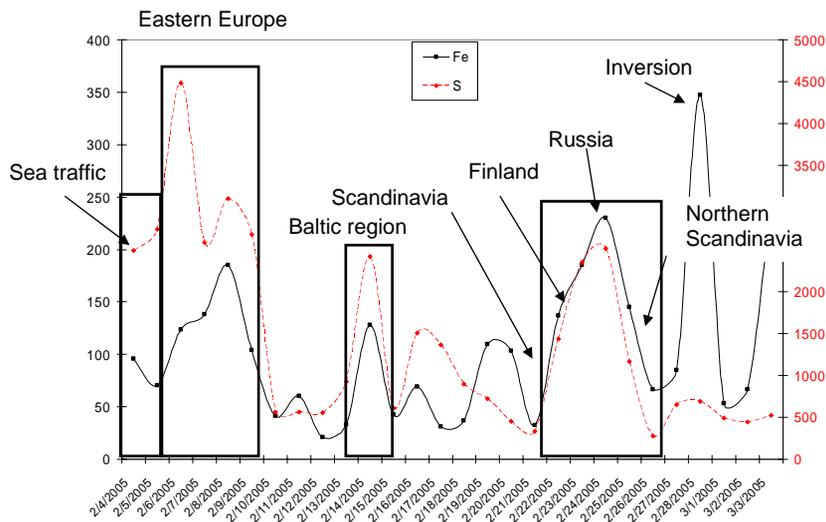
Fig. 3. The S and Fe concentration at the Femman measurement site given on a daily basis together with indications of the possible origin of the air masses. The inversion period between 27 and 28 February is indicated in the figure.