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Association between PM_{10} mass concentration and wind direction in London

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Abstract

A statistical association was found between PM_{10} concentration and wind direction in London and Rochester. Results indicate that PM_{10} levels were 10.4 μg/m^3 (30.7%) above the average when air came from the ESE sector. The possible impact on particle loading due to changes in wind direction is discussed. Copyright © 2006 Royal Meteorological Society

Keywords: PM_{10} mass concentration; air mass back-trajectories; local and regional contribution

1. Introduction

The European and UK Air Quality Objectives (AQO) have set a limit for PM_{10} (particles with diameter equal to or less than 10 micrometres) of 35 exceedances per year of 50 μg/m^3 over a 24-h period, and 40 μg/m^3 maximum for the annual mean to be achieved by 2005.

The origin of PM_{10} episodes in the United Kingdom has been studied to define the driving processes and a significant non-local component has been associated when high PM_{10} levels occur (Harrison *et al*., 1997; Malcolm *et al*., 2000; Smith *et al*., 2001). In a recent study, Stedman (2002) applied the receptor modelling technique to explain the downward trend on PM_{10} observed for the years 1992–2000 in several cities of the United Kingdom and it was concluded that the reduction of secondary particles were the main cause of the decline at London Bloomsbury. However, despite the decreasing trend, an important number of exceedances still occur in London, as Figure 1 shows.

The reasons for the reported trend on PM_{10} levels are still unclear. Is the decline the result of local abatement measures and vehicle and fuel improvements, or have episodes of a non-local nature become less frequent? How significant is the regional component when high PM_{10} levels occur?

The main objective of this work is to seek a relationship between PM_{10} mass concentration and wind distribution in London and a rural site in the United Kingdom. Specific programs and statistical techniques were applied to databases of PM_{10} mass concentration in conjunction with 5-days air mass back trajectories. Special attention was given to the London Marylebone site due to the high levels of pollution observed several times during the study period.

1.1. The monitoring network of PM_{10}

Databases of PM_{10} mass concentration (μg/m^3) were gathered from the Department of the Environment, Transport and the Regions (DETR) network from January 1996 to May 2002 at 12 monitoring sites (Figure 2). The UK network uses the Tapered Element Oscillating Microbalance (TEOM) analyser for measuring mass concentration of particles, which is an equivalent method according to the First Daughter Directive 1999/30/CE (DD1). The use of TEOM has important advantages (data is provided on an almost real-time basis and is a cost and labour-effective method), but also disadvantages due to the operational temperature (50 °C) that generates losses of volatile organic compounds and therefore readings are generally lower than the reference method. It is reported (Chow, 1995; Charron *et al*., 2004) that despite much effort, there is no correction factor that can be applied with certainty. Currently, the general agreement is to multiply the TEOM data by a factor of 1.3 to compensate the loss of volatile organic compounds. The results and conclusions of this study are based on TEOM raw data.

2. Results and discussion

2.1. Descriptive statistics of PM_{10} mass concentration

Seasonal average concentrations of PM_{10} from January 1996 to May 2002 are plotted in Figure 3; for practical

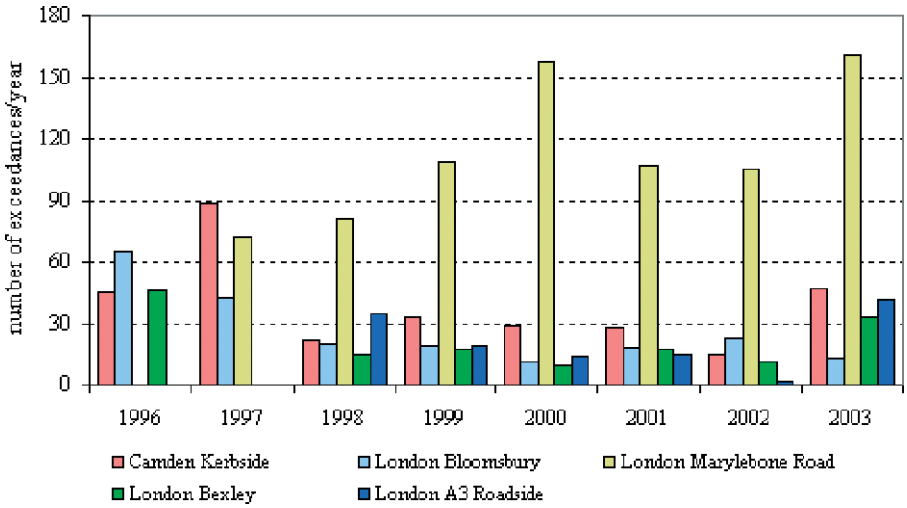

Figure 1. Annual exceedances of PM_{10} in excess of 50 $\mu g/m^3$ over a 24-h period in London

Site	Code	DETR Classification
1 London Hillingdon	HIL	Suburban
2 London A3 Roadside	LA3	Roadside
3 Sutton roadside	SUT	Roadside
4 London Eltham	ELT	Suburban
5 London Bexley	BEX	Suburban
6 Rochester	ROC	Rural
7 London Brent	BRE	Urban background
8 London Kensington	KEN	Urban background
9 London Marylebone Road	MAR	Roadside
10 London Bloomsbury	BLO	Urban centre
11 Haringey Roadside	HAR	Roadside
12 Camden Roadside	CAM	Kerbside

Figure 2. Monitoring sites of PM_{10} in London and the rural site in the southwest of the United Kingdom

purposes the monitoring sites were sorted according to DETR classification. The PM_{10} concentration showed a general decrease with increase in the distance of the monitoring site from the main source (i.e. vehicle exhaust and traffic-related emissions). As the figure depicts, the higher average levels were measured at the kerbside site with exceptions observed in winter 1996, summer 1999, autumn 2001 and winter 2002 when the concentrations measured at the roadside sites were higher. These exceptions were mainly driven by the Marylebone site data that will be discussed in detail later. On the other hand, the lower concentrations mainly corresponded to the rural site Rochester (ROC) showing minimum differences with the urban background and/or suburban sites. ROC is located in the southeast coast of England and because of its position has a great possibility of receiving air masses influenced by continental emissions. Actually, the average concentration in ROC was 18.2 $\mu g/m^3$, i.e. nearly twice the European natural background concentration for PM_{10} (7.0 ± 4.8 $\mu g/m^3$) reported by Van Dingenen *et al.* (2004) and may indicate a significant component of imported particles at this site.

Table I summarises the descriptive statistics for the PM_{10} mass concentration in all the monitoring sites. The average concentrations fluctuated from 34.9 $\mu g/m^3$ in MAR to 18.2 $\mu g/m^3$ in ROC. The maximum concentrations have reached levels of 378 $\mu g/m^3$ (BLO), 420 $\mu g/m^3$ (ELT), 756 $\mu g/m^3$ (SUT), 775 $\mu g/m^3$ (BEX) and 801 $\mu g/m^3$ (MAR). The second maximum was generally close to the first maximum, but these high values constituted less than 5% of the data, as indicated by the p95 column. The next column shows that 90% of the concentrations were below 50 $\mu g/m^3$ in all sites but MAR. The MAR sampler is located near a canyon intersection and therefore the wind flow has a significant influence on dispersion and concentration of pollutants (Scaperdas and Colvile, 1999). The relationship between PM_{10} mass concentration and wind distribution in MAR is discussed later in this work.

2.2. PM_{10} trend

A downward trend in the PM_{10} concentration has been observed for several urban background sites in the United Kingdom including London BLO for the 1992–2000 period and has been explained by a reduction of secondary particles (Stedman, 2002). In this work, we examined the database from January 1996 to May 2002 by regression analysis (Pearson coefficient with 95% confidence level) looking for a

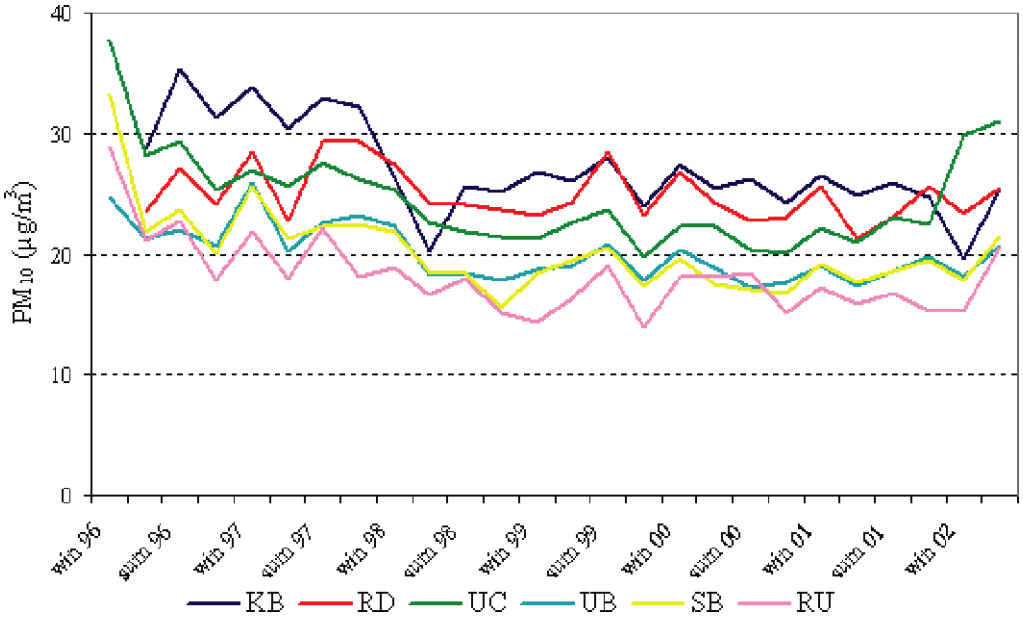

Figure 3. Seasonal average PM_{10} mass concentration from winter 1996 to spring 2002 in several sites of London and a rural site in the United Kingom. *KB = kerbside*; *RD = roadside*; *UC = urban centre*; *UB = urban background*; *SB = suburban* and *RU = rural*. *Winter is January to March; Spring is April to June; Summer is July to September and Autumn is October to December*

Table I. Descriptive statistics for PM_{10} mass concentration in several sites in London and a rural site in the southeast of the United Kingdom. (January 1996 to May 2002). (pn = percentile n)

	Descriptive statistics (µg/m³ of PM_{10})									
Site code	**Max**	**2nd Max**	**p95**	**p90**	**p75**	**p50**	**Ave.**	**p25**	**Min.**	**Slope (µg m^{-3}/y)**
CAM	296	228	54	45	34	24	27.1	17	1	−1.42
SUT	756	733	44	36	26	19	21.4	13	1	—
LA3	262	213	48	40	29	20	22.6	13	1	−1.90
HAR	333	293	46	38	27	20	22.6	14	1	−0.88
MAR	801	800	66	57	44	31	34.9	22	1	—
BLO	378	349	56	45	31	22	26.0	16	1	—
KEN	265	245	44	36	25	18	21.1	13	1	—
BRE	244	235	40	32	23	16	18.6	11	1	—
BEX	775	637	46	37	25	17	20.3	12	1	—
ELT	420	335	38	31	22	16	18.3	12	1	—
HIL	280	227	46	38	27	18	21.2	12	1	—
ROC	298	284	38	31	22	16	18.2	11	1	—

Minimum limit of TEOM = 0.01 µg/m^{-3} with a precision of ±1.5 µg for 1 h average.

tendency in the concentrations of PM_{10}. The results indicate a negative coefficient (i.e. decrease) for 11 of the 12 sites; nevertheless, only CAM, LA3 and HAR sites showed significant regression coefficients (R^2 = 0.69, 0.86 and 0.68 respectively), indicating that PM_{10} reduction has been more effective in the sites near vehicle emissions. The last column of Table I contains the calculated slope for sites with statistical significant results. The slight increase in concentrations of PM_{10} observed for several sites in the last months of 2001 and the beginning of 2002 can explain the discrepancy with the results reported by Stedman and furthermore, can indicate a reverse of the downward trend. The importance of a better understanding of the reasons that have driven the trend (or the lack of it) is clearly required to be able to predict future PM_{10} concentrations.

2.3. Relationship between PM_{10} levels and wind direction

Databases containing the information of 5-day air mass back trajectories arriving at MAR and ROC (1200 h and 950 hPa) from January 1996 to May 2002 were obtained from the British Atmospheric Data Centre. The databases were divided into eight sectors depending on the path prior to arriving at the sites (Table II), and descriptive statistics of PM_{10} concentrations was calculated for each sector. Results for MAR showed that concentrations of PM_{10} were 30.7% (equivalent to 10.4 µg/m^3) above the average concentration when air came from the ESE (91–135°), and 27.0% (equivalent to 9.1 µg/m^3) when air came from the SSE (136–180°) sectors. Both sectors correspond to air masses passing over the PM_{10} high-emission region

Table II. Classification of wind direction

Wind direction	Degrees	Description
NNE	0–45	Air mass travelling over the Arctic and northeast England
ENE	46–90	Air mass travelling over northeast England
ESE	91–135	Air mass travelling over eastern Europe
SSE	136–180	Air mass travelling over eastern-central Europe
SSW	181–225	Air mass travelling over western Europe
WSW	226–270	Air mass with a maritime influence and over southwest England
WNW	271–315	Air mass travelling over the Atlantic and northwest England
NNW	316–360	Air mass travelling over the Atlantic and north England

of eastern and central Europe (ApSimon *et al*., 2001), resulting in an imported pollution to the United Kingdom. These results are in agreement with Smith *et al*. (2001), who found an additional peak concentration of PM_{10} (although higher) of 15–20 $\mu g/m^3$ in three sites in London when air came from 120–160° during 1995–1997. On the other hand, we found that the lower concentrations of PM_{10} were associated with the NNE (0–45°) and NNW (316–365°) sectors that are mainly influenced by local sources. The western winds (WNW and WSW) showed the highest frequency (accounting for nearly 50%), and the lowest frequency corresponded to the southeast quadrant (nearly 12%). Table III summarises the results of the full 7-y period for London MAR; it can be seen that average PM_{10} concentration for the southeast quadrant, ESE and SSE (covering 91–180°), was around 43 $\mu g/m^3$ with a maximum of 85 $\mu g/m^3$. Similar associations between PM_{10} mass concentration and wind distribution were found in the rural site ROC where the PM_{10} average levels were 45.0 and 28.3% higher when wind came from the ESE and SSE respectively (Table IV). In summary, the results obtained for both sites provide strong evidence that concentrations of PM_{10} are significantly influenced by long-range transport contributions, independent of local emissions and control strategies.

Examination of the wind distribution during the period 1996–2002 showed variation during the study period; at the London MAR site the ESE wind showed a statistically significant decrease (Pearson coefficient with 95% confidence level) changing from 9.7% in 1996 to 4.5% in 2002, and the WSW wind showed an increase from 18.4% in 1996 to 34.1% in 2002 (Table V). In the rural site, a significant decrease was observed for the ENE wind direction (15.8% in 1996 to 9.6% in 2002) and an increase in the WSW wind (19.6% in 1996 to 31.7% in 2002) (Table VI).

In the light of possible climate change and the impact on wind distribution and therefore on particle loading, an accurate distinction between UK and non-UK sources of PM_{10} is essential for an effective control of particulate matter concentration. The next examples are taken from September and July 1999 for

Table III. Descriptive statistics for PM_{10} average mass concentration categorised by wind direction at London Marylebone (January 1996 to May 2002)

		PM_{10} mass concentration ($\mu g/m^3$)						
Wind direction	**Frequency (%)**	**Max**	**90th percentile**	**75th percentile**	**50th percentile**	**Average**	**25th percentile**	**Min**
NNE	6.1	42.3	32.5	28.4	24.0	24.9	20.1	14.0
ENE	11.4	57.5	39.4	33.3	29.9	30.3	25.1	12.0
ESE	6.8	85.0	59.3	48.2	43.6	43.8	35.1	26.3
SSE	8.8	85.0	55.5	49.4	44.0	42.8	33.0	22.0
SSW	10.4	71.0	53.0	41.0	35.2	36.2	29.6	13.0
WSW	26.5	64.8	43.2	39.1	34.5	34.1	28.4	17.5
WNW	22.7	55.0	39.8	34.6	30.1	30.9	25.6	15.0
NNW	7.3	64.0	34.2	30.9	25.9	28.1	23.2	14.7

Table IV. Descriptive statistics for PM_{10} average mass concentration categorised by wind direction at Rochester, southeast England (January 1998 to May 2002)

		PM_{10} concentration ($\mu g/m^3$)						
Wind direction	**Frequency (%)**	**Max**	**90th percentile**	**75th percentile**	**50th percentile**	**Average**	**25th percentile**	**Min**
NNE	5.6	29.5	17.9	16.0	13.9	14.3	11.4	9.0
ENE	9.6	29.8	24.3	21.0	18.0	17.9	14.5	9.9
ESE	6.3	40.7	32.1	29.3	24.3	25.2	20.6	15.0
SSE	4.0	40.5	35.9	27.0	22.8	23.1	17.5	10.0
SSW	10.0	34.0	21.3	18.7	15.3	15.9	13.2	4.0
WSW	29.9	24.3	19.9	17.0	15.0	15.2	13.3	9.1
WNW	26.3	24.0	20.0	17.3	15.0	15.6	13.5	11.0
NNW	8.3	28.0	23.2	18.5	14.3	15.6	11.8	9.5

Table V. Annual average frequency of wind direction distribution at London MAR site (1996 to 2002)

	Wind direction (%)							
Year	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
1996	8.6	16.1	9.7	9.8	8.9	18.4	20.1	8.4
1997	5.4	14.4	8.5	9.7	10.8	26.6	18.5	6.1
1998	5.7	9.1	4.7	8.2	10.2	28.9	25.4	7.9
1999	5.0	9.1	6.9	7.9	10.8	27.1	26.4	6.9
2000	5.7	8.7	4.0	7.9	13.4	30.1	24.0	6.1
2001	6.6	12.6	6.5	7.9	8.2	24.3	25.0	8.9
2002	4.7	8.5	4.5	8.7	10.1	34.1	22.6	6.8

Table VI. Annual average frequency of wind direction distribution at Rochester site (1996 to 2002)

	Wind direction (%)							
Year	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
1996	8.1	15.8	8.8	4.3	7.0	19.6	23.6	12.8
1997	6.2	13.6	8.1	4.9	9.8	28.6	21.0	7.8
1998	5.5	8.6	6.2	3.8	9.5	31.1	27.7	9.2
1999	5.1	9.3	6.9	3.7	9.5	30.0	27.2	8.5
2000	5.3	8.4	4.5	3.4	12.8	32.6	26.6	8.4
2001	7.4	12.9	8.3	4.8	9.2	24.7	26.6	8.8
2002	6.6	9.6	7.9	5.9	9.4	31.7	21.3	7.6

illustrating the relationship between mass concentration of particles and wind direction.

The maximum concentrations of PM_{10} that took place in September 1999 had a significant chance of having a significant non-local component. The high concentrations were remarkable in MAR but other sites also showed unusually high concentrations. During this month, the wind distribution was composed of 39.1% of wind flowing from the WSW, 15.3% from the SSW, 14.4% from the SSE and 12.0% from the ESE (that are percentages above the average for these sectors), while the wind flow from NNW, NNE and ENE was negligible. Figure 4(a) depicts the daily variation of PM_{10} and $PM_{2.5}$ from the 17 to 22 of September 1999, illustrating how the PM_{10} concentration built up as the wind flow switched from WSW towards the ESE sector. High concentrations were sustained with winds coming from the SSW direction, which is the third highest sector in terms of average particle level. The fine fraction ($PM_{2.5}$) was 46.8% of PM_{10} on average. On the other hand, Figure 4(b) depicts the daily variation when the PM_{10} mass concentration can be attributed mostly to local sources (wind distribution was composed of 26.8% of wind

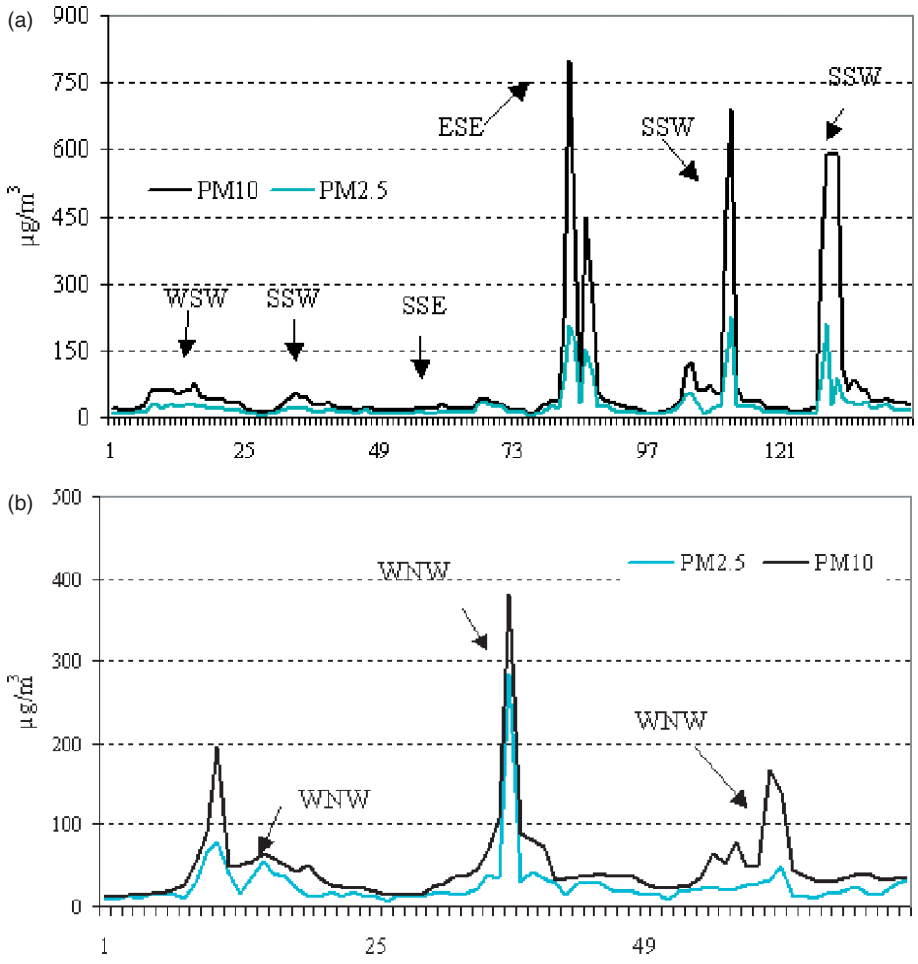

Figure 4. Daily variation of particle mass concentration (µg/m^3) in London Marylebone from 17 to 22 of September 1999 (A), and from 13 to 15 of July 1999 (B). Wind direction is also indicated

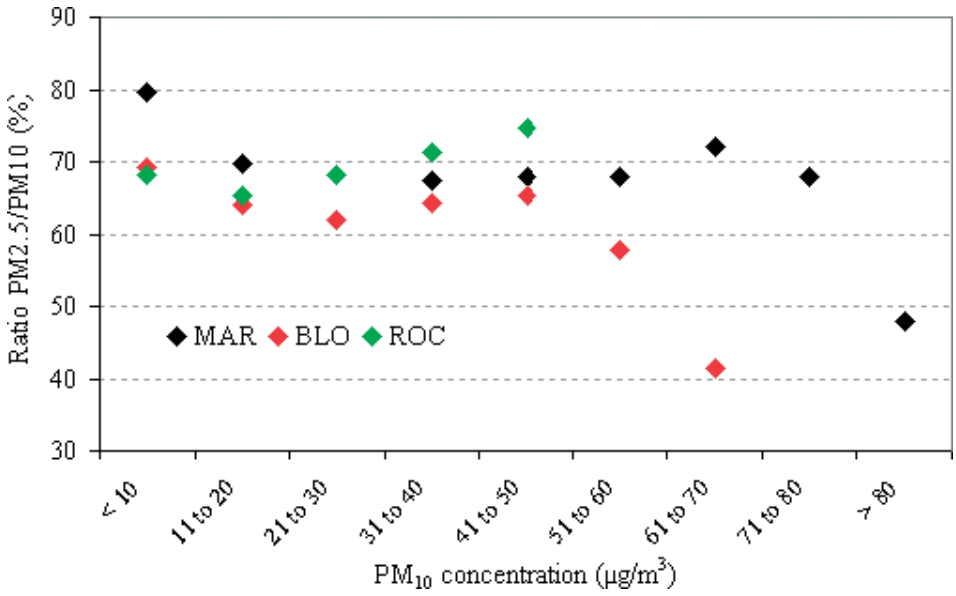

Figure 5. $PM_{2.5}/PM_{10}$ ratio categorised by PM_{10} mass concentration

coming from WNW, 25.3% from ENE and 25.0% from WSW); both fine and coarse particles showed a more correlated variation representing a typical vehicle exhaust derived pollution where the fine fraction was 60.0% of PM_{10}.

2.4. $PM_{2.5}/PM_{10}$ ratio

The ratio $PM_{2.5}/PM_{10}$ was obtained by increments of 10 µg/m^3 of the PM_{10} for MAR, BLO and ROC (Figure 5). The rural site (ROC) showed higher ratios (ranging from 65.4 to 74.6%) compared with the urban sites and a general increment of the $PM_{2.5}$ as the PM_{10} concentration increased. There were two wind directions generally associated with the higher ratios, the SSE and the ENE. Taken together, results may indicate the importance of transported secondary aerosols as one of the main sources of particles in this site.

Within the urban area, the higher proportion of fine particles corresponded to MAR (roadside site) compared with BLO (urban centre site), as a result of their proximity to vehicular emissions. As Figure 5 describes, both sites showed a drop in the proportion of fine particles for the last two ranges of PM_{10} concentrations (e.g. above 51 µg/m^3 at BLO, and above 71 µg/m^3 at MAR), indicating that fine particles for the highest PM_{10} concentrations accounted for less than 50%. In these cases, winds coming from WNW, SSW and ESE showed the main frequency; the first wind direction is associated with local sources of particles, while the SSW and ESE are sectors related to non-local sources implying a long-range transport contribution. Currently, we are analysing the effect of wind speed on particle concentration to elucidate the contribution of re-suspended particles on the build up of high PM_{10} concentrations.

3. Conclusions

Throughout this article, we have shown the effect of wind distribution on PM_{10} concentration in London Marylebone and ROC sites. The results in MAR indicated that concentrations of particles were 30.7% higher when air came from the ESE (91–135°) direction and 27.0% higher when the wind came from the SSE (136–180°) direction that correspond to air masses travelling over high PM_{10} emission regions of Europe. Both SSE and ESE directions had the same effect in ROC, giving strong evidence of a long-range transport contribution.

Significant changes on the wind distribution were detected; a decrease in the ESE direction (9.7% in 1996 to 4.5% in 2002) and an increase in the WSW direction (from 18.4% in 1996 to 34.1% in 2002). If emissions have remained constant over the study period, a change in the prevailing wind direction will itself cause a change in the particle loading at the sites investigated; here we suggest that part of the decreasing trend is due to the fact that London has sampled cleaner background air as we have progressed from 1996 to 2002. How the potential modifications to the wind distribution affect the particle concentration, either by decreasing or increasing particle loading, are still far from certain. Further detailed modelling is underway.

Inclusion of parameters like wind speed and vehicle emissions will improve the de-coupling of local *versus* non-local sources, and therefore the understanding of the causes driving high particulate matter levels.

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