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COMBINING MODELLING AND MONITORING TO ESTIMATE FUGITIVE RELEASES FROM A HEAVILY INDUSTRIALISED SITE

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Abstract: Ambient air-quality data contains detailed information about individual sources that is currently under-exploited. This study examines ambient measurements of fine particulate matter (PM_{10}) from a complex industrial site, in order to show how ambient concentrations depend on factors related to dispersion - such as wind speed and wind direction, and on different levels of source activity - such as time-of-day and day-of-week. When this additional information is combined with inverse-modelling techniques, it can be used to attribute PM_{10} impacts to individual sources. The information can also be used to comprehensively verify the performance of atmospheric dispersion models.

Key words: *particulate matter, inverse-modelling, fugitive source, conditional analysis*

INTRODUCTION

The '*AirTrack*' project (http://airtrack.lancs.ac.uk/) is funded by the UK's Natural Environment Research Council and is working to develop and disseminate 'smarter' methods for analysing modelled and measured ambient air-quality data. These novel methods permit air-quality data to serve a wide range of applications, including source apportionment and detailed assessments of model and source performance. This paper presents an *AirTrack* case study of a multi-source industrial situation in Scunthorpe, UK, where a major steelworks adjoins an urban area. This is an area where emissions of fine particulate matter (PM_{10}) from combustion and fugitive sources (e.g. stockpiles and un-paved roads) are contributing to exceedances of PM_{10} limit values. The study focuses on preparing estimates of fugitive PM_{10} releases from storage, handling and vehicle activities, using information from ambient monitoring data.

BACKGROUND

Human exposure to fine particulate matter is associated with morbidity and mortality because of its adverse effect on the respiratory and cardiovascular systems. It has been shown that there is no 'safe-level' below which populations do not experience health effects (Martuzzi *et al.*, 2006). The serious impacts of PM_{10} on human health have led the EU Commission to set strict ambient PM_{10} standards with binding daily, and annual-average, limit values. However, a number of EU countries have not yet complied with these standards; they have asked the Commission for additional time to comply, but these requests have been rejected (EUROPA, 2009). Techniques for attributing ambient concentrations of PM_{10} to individual sources are not particularly well developed (Harrison *et al.*, 2008), but are required so that relevant sources can be controlled. This is particularly important in complex industrial areas where there are fugitive releases of PM_{10} - these tend to be poorly characterised because they are diffuse and commonly overlap other sources.

The town of Scunthorpe has a population of approximately 70,000; on its eastern side it has a major industrial area that includes an iron and steel works. There has been a history of elevated concentrations of air pollution around Scunthorpe, due to the dusty nature of steel production and the proximity of the industrial and urban areas. The highest monitored air-quality impacts for PM_{10} currently occur at a monitor adjacent to a small number of houses at the village of Santon, which lies north-east (down-prevailing wind) of the steelworks and next to the steelworks site boundary. In 2006, Santon exceeded the daily air-quality limit value on 158 days, and in the first 7 months of 2009 Santon recorded 116 exceedances of the daily limit values. These exceedance rates are substantially more than the 35 exceedance days each year that are permitted. There are a number of fugitive sources on the site that are thought to contribute to the high number of exceedances. In particular, there is a network of unpaved dusty roads that are used by many heavy-goods vehicles and nearby stockpiles that are used for open storage and handling of industrial raw materials.

METHODOLOGY

Our approach combines and builds on previous techniques for attributing fugitive sources of PM_{10} to individual sources, so that estimates can be made of their emissions. We demonstrate that detailed and source-specific information can be extracted from ambient data if hourly concentrations are analysed 'conditionally' i.e. for particular ranges of wind speed, wind direction and time-of-day/week – this information can be associated with elevated impacts from specific sources. By contrast, conventional analyses of air-quality tend to use all available data i.e. all wind speeds, directions and times of day/week (Carslaw and Ropkins, 2010) – this is not as effective at distinguishing impacts from individual sources.

We combine modelled and monitored data in an iterative process by using inverse modelling techniques (e.g. Mensink *et al.*, 2007). We use bi-polar plots for conditioning the data by factors related to atmospheric dispersion and source-activity levels (e.g. Barratt and Fuller, 2008). These plots build on the concept of using a polar plot (or pollution rose) to show how concentrations vary with direction, by adding a second variable e.g. wind speed or time-of-day.

A multi-stage process of estimating and refining emissions from fugitive sources is described and then demonstrated below:

1. Existing emission inventories for industrial combustion point sources, urban, domestic and background sources are used to model hourly ambient concentrations of PM_{10} at Santon.

2. Predicted hourly concentrations from [1] are subtracted from hourly monitored concentrations on the assumption that the remaining, or residual, concentrations are due to impacts from on-site fugitive sources. Hourly residuals are analysed conditionally using bi-polar plots, in order to characterise how 'missing' releases depend on activity levels and dispersion conditions.

3. Information from [2] on the dispersion and activity-level dependencies of residual concentrations are used to infer the locations and characteristics of likely fugitive activities e.g. the directions of fugitive activities, and if fugitive activities are related to particular hours/days or particular wind speeds/directions. Aerial photographs and site maps are used to identify potential sources.

4. The inferred locations and characteristics are used to estimate the positions, magnitudes and timings of fugitive emissions based on USEPA emission factors. Their impacts at Santon are then modelled using the ADMS dispersion model.

5. Estimates of fugitive impacts from [4] are verified by comparing modelled fugitive concentrations with inferred fugitive concentrations from [2]. Conventional verification methods use statistics that indicate the magnitude of discrepancies only. However, a more comprehensive method is used here to verify emissions, by comparing bi-polar plots of measured and modelled concentrations. This not only shows the magnitudes of discrepancies, but also their directions and their dependence on wind speed and time-of-day, so that the inventory can be refined on the basis of these characteristics.

RESULTS

Fig. 1 contains 2 bi-polar plots which uses a colour ramp to show PM_{10} concentrations monitored at Santon during 2006. The inner plot shows how concentrations vary with wind direction and wind speed (radial axis), and the outer plot shows how they vary with wind direction and time-of-day (radial axis). These 'signatures' of PM_{10} concentrations indicate that raised impacts are generally confined to working hours and increase notably with strong winds. The plots are superimposed on a map at the position of the Santon monitor.

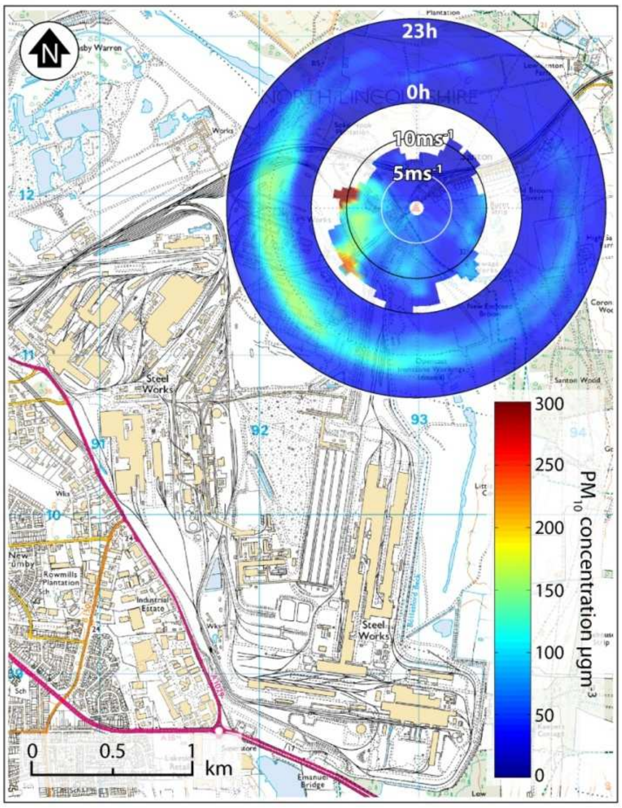

Fig. 1 Bi-polar plot of monitored hourly PM_{10} at Santon during 2006.

As described in Stages 1 and 2 above, the contribution of fugitive sources to PM_{10} at Santon was estimated by subtracting a modelled contribution of known 'existing' sources (Fig. 2a), from monitored concentrations at Santon (Fig. 1). The residual concentrations (Fig. 2b) are the discrepancies between measurements and modelling, and can be interpreted as an 'inferred' fugitive contribution.

The positive residuals on Fig. 2b show that the initial (Stage 1) modelling of PM_{10} at Santon greatly under-estimated PM_{10} impacts. In particular, it shows that the greatest under-estimates occur to the west and south-west of Santon, corresponding to the general direction of the steelworks. In order to reduce these discrepancies, the inventory of PM_{10} releases must be refined to include the inferred fugitive sources of PM_{10}. Fig. 2b is used to characterise how those fugitive sources depend on wind speed, wind direction and time of day.

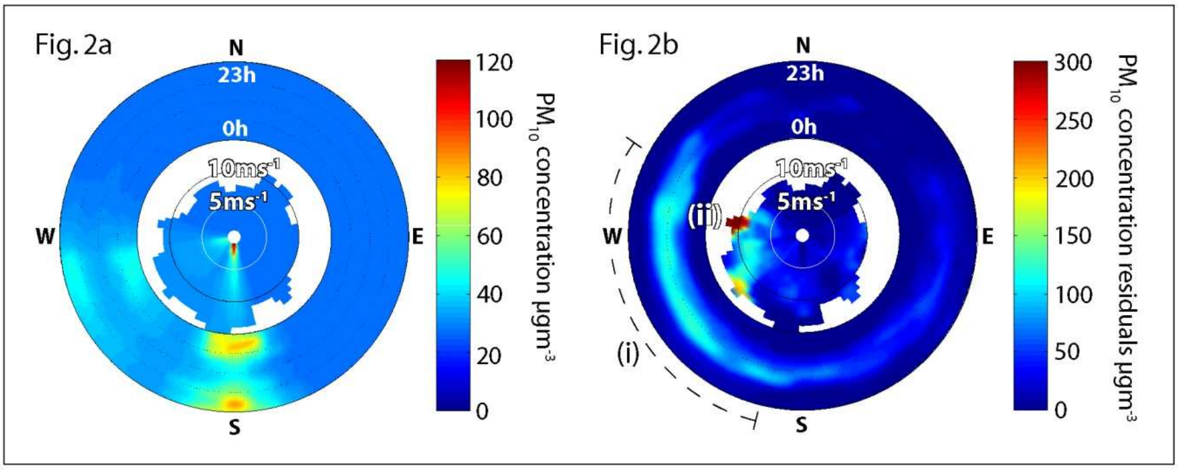

Fig. 2 Bi-polar plots of (a) modelled hourly PM_{10} using 'existing' sources, and (b) hourly PM_{10} concentration residuals

One feature of the residual plot (Fig. 2b) is the large swathe (covering directions from c. S to c. NW) of positive residuals, where modelling under-estimates observed concentrations during 'working-hours' i.e. between approximately 6am and 6pm – feature (i). The time dependency of this feature suggests that residual concentrations are related to periods of activity e.g. traffic and/or handling of materials during working hours, and are not especially related to meteorological conditions e.g. wind raising of dust from stockpiles.

There is an additional smaller feature (ii) of model under-estimation in a WNW direction that contains discrepancies > 300 μgm^{-3} for periods of high-wind speeds. The residual plot also indicates that residual concentrations within feature (ii) continue to increase with wind speed, which supports wind ablation as an important mechanism for delivering raised impacts.

Using these activity- and dispersion-related dependencies, potential sources of fugitive PM_{10} releases were identified on the steelworks site from site maps and aerial photographs (Fig. 3). We identified 3 sources – 2 area sources which are shown as hatched areas and include an area of coal-handling beds and a slag processing plant, and 1 line source which is shown as a dashed line and is an un-paved slag-haul road.

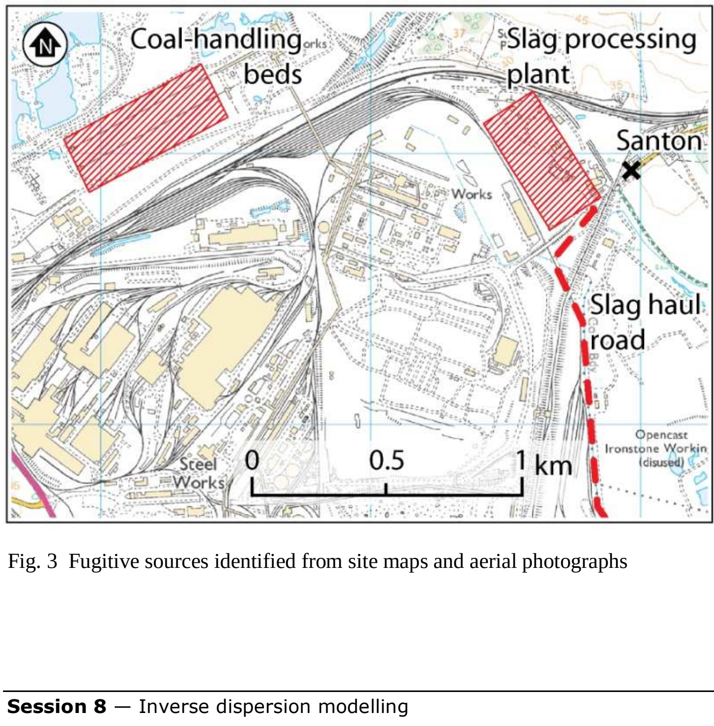

Fig. 3 Fugitive sources identified from site maps and aerial photographs

Information on the activities at the coal-handling beds, slag-processing plant and slag-haul road was combined with USEPA emission factors (USEPA, 1995), in order to estimate the fugitive emissions from these sources. Particular emphasis was placed on re-creating the temporal and positional characteristics of their fugitive emissions. The estimated fugitive emissions from these 3 sources were input to the ADMS dispersion model in order to calculate their impacts on ground-level concentrations of PM_{10} at Santon.

The results of the fugitive-source modelling were compared to the inferred fugitive contribution in 2 stages. Firstly, we used conventional statistical methods of comparing modelled and monitored data. However, conventional methods such as quantile-quantile plots and bulk statistics like percentiles (CERC 2007) do not provide a detailed account of model performance. This is because they tend to compare statistics that do not describe model performance for particular dispersion conditions or stages of activity cycles. Secondly, we used a more comprehensive 'conditional validation' to verify the emissions inventory and dispersion modelling, by checking if temporal and directional features of the ambient data are re-produced by the model.

An initial verification is made between predicted fugitive impacts and the inferred fugitive contribution. A final verification is made by comparing the results of modelling PM_{10} concentrations at Santon using the complete inventory – urban, domestic, industrial-combustion and industrial-fugitive, with monitoring (Fig. 1). Statistics are compared in Table 1.

Table 1 Summary statistics of PM_{10} modelling and monitoring

PM_{10} µgm^{-3}	Annual average	100th %ile	99th %ile	90th %ile	50th %ile
Monitoring	59.2	958.0	382.0	127.2	36.0
Modelling	56.4	1101.7	358.8	129.4	31.0
Discrepancy (%) from modelling	-4.7	15.0	-6.1	1.7	-14.0

DISCUSSION

By including fugitive sources in the inventory of PM_{10} releases, the numerical agreement between modelling and monitoring is greatly improved. Furthermore, by comparing corresponding bi-polar plots for modelling and monitoring (Fig. 1), it can be seen that the patterns of raised impacts for different dispersion conditions and activity-cycles are reasonably reproduced. For example, the dependence of raised impacts on wind speed and time-of-day from modelling agrees broadly with the observed dependence. Given the good agreement obtained for different wind directions, time-of-day, wind speeds and percentiles, considerable confidence can be placed in the overall emissions inventory. A robust inventory means that it is possible to assess the contribution of different sources by modelling their combined impacts and then separating out the incremental impacts of each source. This will allow the most polluting sources to be identified and targeted for control. Analysis shows that slag-haul road emissions dominate fugitive PM_{10} impacts at Santon (Fig. 4).

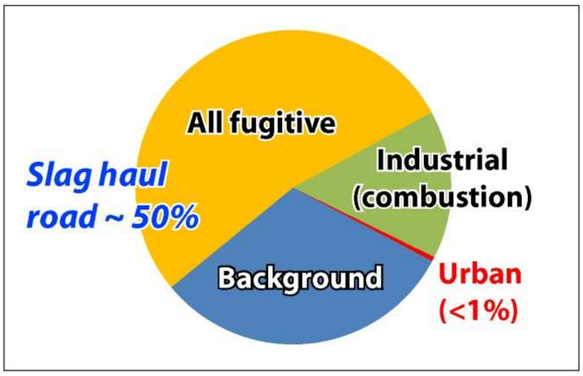

Fig. 4 Modelled source attribution of impacts contributing to PM_{10} exceedance days at Santon.

CONCLUSION

Bi-polar plots are an extra and useful tool that can be used when analysing or comparing air-quality modelling and monitoring data, because they combine a number of variables that are commonly examined independently. For example, bi-polar plots of concentration residuals describe the magnitude of inferred 'missing' sources and their dependence on time-of-day and wind speed. In addition, they show the direction of the missing contribution from the monitor so that information on the nature of the release can be linked to individual polluting activities and sources. Bi-polar plots are useful for studies of model verification, and when combined with inverse-modelling techniques, can be used to help with source attribution.

These methods for conditionally verifying model performance are more comprehensive than conventional methods because they check if the dispersion model produces the right answer for the 'right reasons'. In particular, they provide a means of interrogating the meteorological and activity-level mechanisms that deliver high impacts. This means that control measures to reduce pollution impacts can be applied more promptly and confidently.

A robust inventory is important for identifying the most polluting sources to be targeted for control. A robust inventory is also important if the model is to be used for checking how impacts from a source may vary in future e.g. as a result of specific conditions that deliver raised impacts becoming more frequent under climate change. For example, raised impacts from open storage of raw materials tend to occur by wind ablation during high-wind-speed events. It follows that if the wind-speed dependency of impacts is not correctly reproduced by the model, then the impacts of that source modelled for a future climate with more frequent high-wind speeds may be under-estimated.

The techniques have been demonstrated here for a steelworks site, but could also be applied in other regulated industrial situations where there are similar issues, i.e. where there are other wind-ablated sources such as landfills or ash-mounds.

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