AIR POLLUTION IMPACTS AND SOURCES UNDER A CHANGING CLIMATE: A CASE STUDY FOR SCUNTHORPE, UK

Andrew Malby[1]*, Roger Timmis*[2] *and Duncan Whyatt*[1]

[1]Department of Geography, Lancaster Environment Centre, Lancaster University, UK
[2]Environment Agency, UK

Abstract: Climate change may affect local air quality by altering the emission, dispersion, chemical transformation and deposition of air pollutants. This study evaluates the effects of climate change in a real-life mixed land-use situation where there are adjacent urban and industrial activities and also fugitive emissions from stockpiles and unpaved roads. For this example we show how wind-speed and time-of-day dependent 'bi-polar plots' created from ambient monitoring data can be used to learn more about the nature of sources responsible for exceedances of particulate matter air quality standards, and hence to assess how sensitive their impacts are to climate change. Unpaved roads and wind-blown fugitive sources such as stockpiles and coal handling beds in the industrial area appear to contribute substantially to raised air-quality impacts. The effect of climate change on impacts from these sources may differ from its effect on impacts from conventional combustion sources.

Key words: *particulate matter; fugitive source; climate change; industrial regulation.*

1. INTRODUCTION

Increasing recognition of the interactions between air quality and climate change has prompted studies of the impact of air quality on climate change and more recently, of the impact of climate change on the emission, dispersion, chemical transformation and deposition of air pollutants (e.g. AQEG, 2006). The present study investigates the effect of climate change on plume impacts from different types of polluting activities in a mixed land-use situation. Specifically, it evaluates how climate change may affect dispersion and emissions in a town where there are adjacent urban and industrial sources of air pollutants and additional fugitive sources.

2. BACKGROUND

Plume permits are granted to industrial processes to allow them to operate and release pollutants to the atmosphere under specific, regulated conditions. Plume-impact assessments of these sources are generally based on modelling, and are designed to take into account current climatic variability, i.e. variability in the frequency of dispersion conditions that deliver raised air-quality impacts from different sources. There is a concern that climate change may alter the current variability, so that the dispersion conditions associated with raised impacts occur more often. Consideration should therefore be given to whether modelled plume-impact assessments will need to be modified or 'climate-proofed', in order to provide the same level of protection to sensitive receptors in future. Previously, we have shown that the effect of a change in the dispersion climate on impacts from individual (hypothetical) industrial plumes is highly site-specific (Malby et al., 2007). For example, the effect of climate change varies substantially depending on whether the impacted receptor is located in the near- or far-field and whether pollutants are released from ground-level or elevated sources.

Real-life air-quality management issues, however, are generally associated with more complex source situations, where there are a mix of different source types, i.e. pollutants may be released from traffic, industrial stacks, and fugitive sources, such as stockpiles and unpaved roads. In such complex situations, the combined effects of climate change may be compensatory or additive, i.e. greater impacts from one type of activity may be offset by lesser impacts from another, or otherwise.

Scunthorpe is a relatively discrete town, with a major industrial area (including an iron and steel works) immediately adjacent to an urban area (population ~70,000). In 2005, the local council declared an Air Quality Management Area (AQMA) surrounding the steelworks site because there were too many exceedances of the daily mean standard for fine particulate matter (PM_{10}). In 2008, the AQMA will be extended to also reflect infringement of the annual mean standard for PM_{10}. The highest monitored air quality impacts currently occur at a monitor adjacent to a small number of houses at Santon – located to the east (i.e. down-prevailing wind) of the steelworks, adjacent to the site boundary. In 2006, Santon exceeded the daily air quality limit value on 158 days (35 exceedance days per year are permitted). While combustion sources on the industrial site are likely to contribute to the high number of exceedances of PM_{10} air quality standards at this site, it is thought that fugitive sources also contribute substantially. For example, there is a network of unpaved dusty roads that are used by many heavy-goods vehicles in the industrial area, and also nearby stockpiles for storage of raw materials.

3. METHODOLOGY

Given the complex nature of polluting activities on the steelworks site, and the large number of potential sources of particulate matter e.g. natural and anthropogenic (combustion and fugitive), the precise sources causing raised impacts at Santon are not fully understood. The first part of this study therefore uses a range of novel techniques to examine recent ambient monitoring data from Scunthorpe, in order to learn more about the characteristics of the sources of PM_{10} causing exceedances of air-quality standards, so that these sources may be targeted for improvement.

Monitoring Data

Hourly data can be analysed directionally from concentric bi-polar plots that show how PM_{10} concentrations depend on wind speed, time-of-day or day-of-week. The plots are helpful for assessing if periods of raised particulate impacts are mainly due to dispersion (e.g. greatest under stable or convective conditions), or to particular patterns of activity (e.g. during working hours). We can therefore use bi-polar plot source 'signatures' to infer whether raised impacts are delivered by combustion or fugitive sources, because combustion sources operate continuously, where as fugitive sources (vehicles, stockpile handling) are generally confined to daytime and weekdays only. Given the differential response of different sources of particulate matter to a change in the climate, this is an important distinction to be made.

A useful comparison of the nature of PM_{10} impacts can be made between two monitoring sites: Santon to the east of the steelworks and Rowland Road to the west. Figure 1 shows wind-speed dependent bi-polar plots of PM_{10} monitoring at these sites. They highlight two important features of the data that are common to both monitoring sites: i) directionally, the 'hot-spots' indicate that PM_{10} concentrations are highest when the wind blows from the steelworks, and ii) PM_{10} concentrations are greatest at high wind speeds (the radial wind-speed scale increases from the centre of the bi-polar plot outwards).

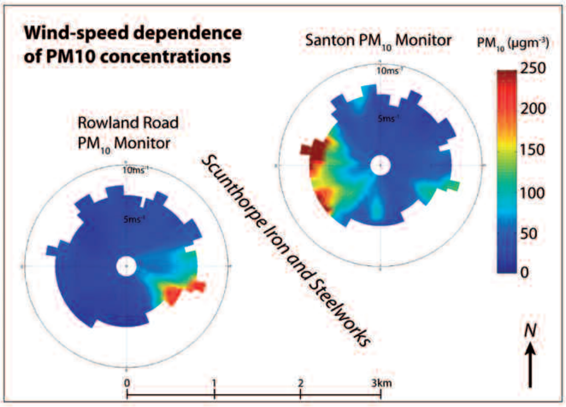

Figure 1. Wind-speed dependence of PM_{10} concentrations at Rowland Road and Santon monitors.

Figure 2 uses bi-polar plots to show how PM_{10} concentrations depend on time-of-day for the same monitoring period and sites (see radial scale on diagram). At Rowland Road raised plume impacts can occur during all hours of the day, but are highest between approximately midday and 4pm. This corresponds to the period of strongest convective heating/turbulence and as such likely represents episodes of 'plume-looping' from elevated combustion sources that operate on a 24-hour 7-days-a-week basis. By contrast, at Santon raised plume impacts are confined to a period between the hours of 6am and 6pm, as defined by a marked 'fall-off' in concentrations before/after these times. This likely corresponds to the period of frequent vehicle and raw material movements, i.e. conventional 'working-hours'. This is reinforced by day-of-week dependent bi-polar plots (not shown) which highlight that raised impacts at Rowland Road occur 7-days per week, whereas those at Santon are confined to Monday-Friday.

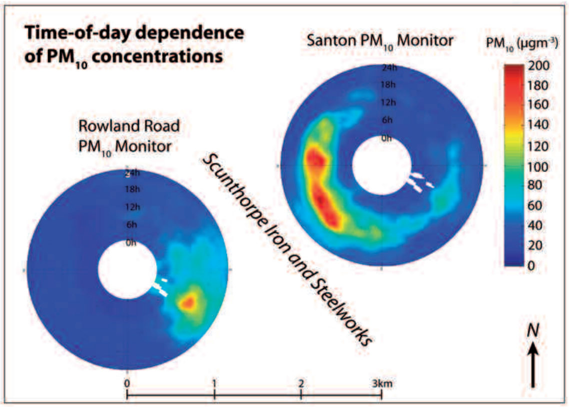

Figure 2. Time-of-day dependence of PM_{10} concentrations at Rowland Road and Santon monitor.

Dispersion Modelling

To be able to assess the effect of climate change on particulate matter impacts in this industrial area, we firstly need to model the present-day situation. Once we have established reasonable agreement between modelling and present-day monitoring, we can then alter the climate and assess how this affects modelled plume impacts. However, analysis and dissection of the ambient monitoring data (in the previous section) suggested that fugitive sources may contribute a substantial proportion of raised impacts. Due to their nature, the magnitude and temporal variability of fugitive releases are generally difficult to quantify and parameterise for the purpose of dispersion modelling.

To further assess the degree to which fugitive sources contribute to raised particulate matter impacts at these monitors, we perform a preliminary modelling exercise (using ADMS-Urban), including in our inventory urban and industrial combustion sources only, i.e. we include no fugitive sources of particulate matter. By modelling with just urban and industrial combustion sources, we can deduct the predictions from observed concentrations in order to estimate the fugitive contribution as a difference. We then consider whether this difference is plausible in terms of its magnitude and its co-variations with bi-variate parameters like direction, wind-speed, time-of-day and day-of-week.

All sources on the steelworks site and other significant industrial sites around Scunthorpe are modelled as individual point sources. Annual-average daily traffic counts and a 'typical' diurnal profile of emissions for each day of the week (created from hourly traffic count data in Scunthorpe) are used to estimate traffic-based emissions along main roads. Emissions from smaller/minor roads, minor industries and agriculture are taken from gridded estimates from the UK National Atmospheric Emissions Inventory (NAEI, 2003). Due to limited availability of emission inventory and ambient monitoring data, the full inventory used as input to the model does not precisely match the year for which PM_{10} monitoring was available. However, we consider the errors associated with this to be small compared to the uncertainties in the emission estimates themselves. Hourly wind speed and direction data are taken from observations at the Rowland Road site and cloud cover from the nearest available record (RAF Waddington, approx. 40km S of study area).

Tables 1 and 2 show summary statistics of preliminary modelling of PM_{10} at Rowland Road and Santon, together with corresponding statistics of PM_{10} monitoring. We compare a range of percentile values that are designed to show how well the model re-creates high and low concentrations. There is a particular emphasis towards high percentiles, given their importance for exceedances of air quality standards. At Rowland Road, percentage errors in modelling of annual percentile statistics are less than 50%. There is no systematic bias towards either under- or over-prediction. At Santon, percentage errors in modelling are larger, and the model consistently under-predicts PM_{10} concentrations. The largest error is in predicting peak concentrations, i.e. 100th and 99th percentiles.

Table 1. Summary statistics of PM_{10} modelling and monitoring at Rowland Road.

PM_{10} μgm^{-3}	Annual Average	100th percentile	99th percentile	90th percentile	50th percentile
Monitoring	29.5	276.0	126.8	56.0	22.0
Modelling	29.5	316.1	67.3	32.3	27.3
% Difference	0%	+ 15%	- 47%	- 42%	+ 24%

Table 2. Summary statistics of PM_{10} modelling and monitoring at Santon.

PM_{10} μgm^{-3}	Annual Average	100th percentile	99th percentile	90th percentile	50th percentile
Monitoring	59.2	958.0	382.0	127.4	36.0
Modelling	41.6	315.5	180.6	65.3	32.2
% Difference	- 30%	- 67%	- 53%	- 49%	- 10%

Model validation is commonly performed by comparing simple bulk statistics like means and percentiles of predictions and observations. However, these bulk methods only give a broad account of model performance, and they do not show specifically which aspects of pollutant emissions and dispersion are modelled more, or less, accurately. For the purpose of assessing the effect of climate change on plume impacts, it is important to know how well a model is predicting different aspects of pollutant emissions and dispersion, so that altered plume impacts are correctly attributed to a change in the frequency of a particular dispersion condition.

With the output from our preliminary modelling, we extend the directional analysis demonstrated with the ambient monitoring data above, to identify why the model under-/over-predicts at the Rowland Road and Santon receptors. We use a combination of monitored and modelled data (and site maps) to highlight sources that are missing from our inventory, i.e. as a form of 'forensic-modelling' (Ferranti et al., *in press*). Specifically, we plot 'monitored minus modelled' concentrations on concentric bi-polar plots for each receptor. These plots of concentration residuals therefore show how discrepancies between modelling and observations vary with direction and with factors related to dispersion (wind speed) and emitting activities (time-of-day).

Figure 3a shows a time-of-day dependent bi-polar plot of ‘monitored minus modelled’ concentrations at Rowland Road. Positive values represent model under-estimation and negative values represent model over-estimation. The largest discrepancies between modelled and monitored concentrations are in the direction of the steelworks site, where there is a general tendency towards under-estimation. Specifically, at approx. 120-degrees, there is a substantial under-prediction (80-100 μgm^{-3}) occuring in the afternoon period. Conversely, at approx. 135-degrees there is an over-prediction (30-60 μgm^{-3}) during the early morning and late night periods. On a wind-speed dependent basis (Figure 3b), discrepancies between modelling and monitoring are greatest at high wind speeds in the direction of the steelworks.

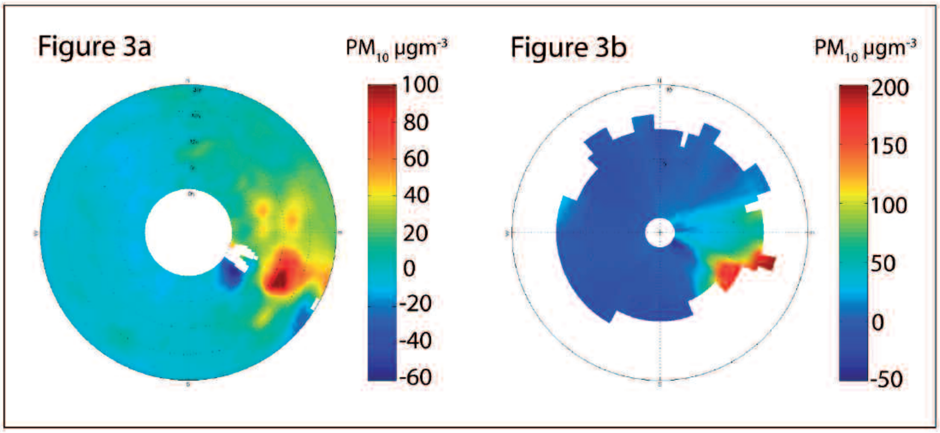

Figure 3. Modelling discrepancies of PM_{10} concentrations on a time-of-day dependent basis (3a) and a wind-speed dependent basis (3b) at the Rowland Road monitor.

At Santon (Fig. 4), there is a similar trend towards general under-estimation of PM_{10} concentrations. In a southerly direction, concentrations are over-estimated during early morning and late night periods (Fig. 4a). Between south-westerly and north-westerly directions, concentrations are under-estimated during ‘working hours’, i.e. between approx. 6am and 6pm. The largest discrepancies are evident by examining wind-speed dependency (Fig. 4b); PM_{10} impacts in a WNW direction are significantly under-estimated (by approx. 800 μgm^{-3}). This suggests that there is a substantial source of particulate matter that is not included in our inventory. The direction of this feature from the monitor (approx. 280-degrees) and the nature of raised impacts, i.e. raised under high wind speeds and between approx. 6am to 6pm Monday-Friday (likely coinciding with periods of increased material disturbance), supports a region of coal handling beds as a potential source of fugitive PM_{10} release. This source can be identified from aerial photography and site maps.

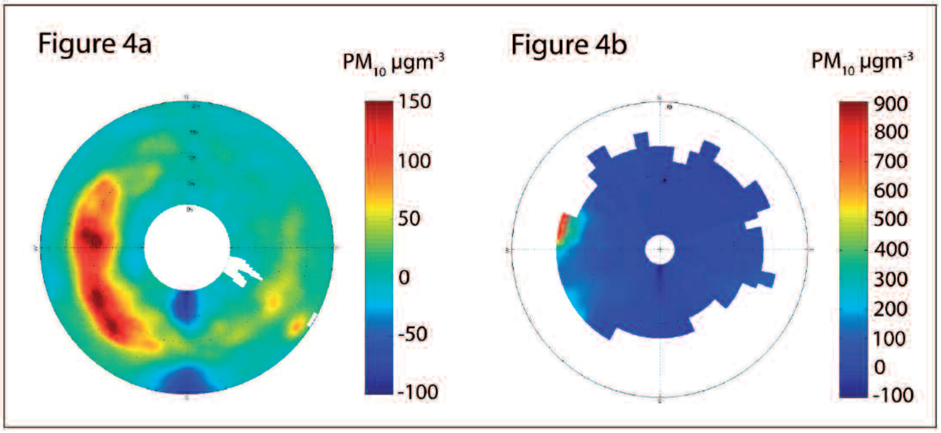

Figure 4. Modelling discrepancies of PM_{10} concentrations on a time-of-day dependent basis (4a) and a wind-speed dependent basis (4b) at the Santon monitor.

4. FURTHER WORK

To date, we have shown how using ambient air-quality monitoring data and dispersion model output together in bi-variate polar plots, can teach us more about sources of raised air-quality impacts and model performance. The remainder of this study will explore techniques for modelling fugitive sources where the rate of emission is related to the prevailing meteorological conditions, e.g. moisture and/or wind-speed. We will use a combination of summary statistics and bi-polar plots to identify when the model best re-creates particulate matter impacts.

When we have reasonable agreement between modelled and monitored concentrations, we can then consider the effect of a change in the climate on overall air quality impacts, i.e. fugitive, industrial (combustion) and traffic sources. Generally, the way that climate change alters impacts from combustion sources is by affecting the frequency of local dispersion conditions. However, for fugitive sources, there may be additional mechanisms by which climate change alters air quality impacts in the future, e.g. additional emissions due to windier conditions or drier surfaces. We consider the magnitude of air-quality impact changes due to climate, relative to the magnitude of changes due to intended measures of emission abatement, e.g. sealing of the unpaved dusty road.

5. CONCLUSIONS

This study demonstrates techniques for extracting more information from ambient monitoring data than simple exceedance statistics. These techniques can be used for the purpose of source characterisation and for 'forensic-modelling', i.e. identifying missing sources from an emissions inventory. We will now work on parameterising fugitive releases of PM_{10} that appear to contribute substantially to the high number of air-quality exceedances. We will then be in a position to examine impacts of single and multiple sources under a changing climate.

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REFERENCES

Air Quality Expert Group (AQEG), 2006: Air Quality and Climate Change: A UK Perspective Available from http://www.defra.gov.uk/environment/airquality/panels/aqeg/index.htm

Ferranti, E.J., Whyatt, J.D. and Davison, B. (*in press*) An investigation into the origins of a series of PM_{10} anomalies at a remote location in NW England. Journal of Environmental Monitoring.

Malby, A., Timmis, R and Whyatt, J.D., (2007: The Effect of Climate Change on the Local Dispersion of Air Pollutants. *Proceedings of the 11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.* **1**, 87-91.

NAEI (2003). UK Emission Maps: Area Source Emission Maps and Point Source Files. CD. Also available from http://www.naei.org.uk/data_warehouse.php