Review of Ambient Monitoring Data from Two Sydney Road Tunnels (M5 East & Cross-City)

Final Report

Dr Mark F Hibberd

June 2019

Prepared for:

NSW Roads & Maritime Services on behalf of Advisory Committee on Tunnel Air Quality

Citation

Hibberd, MF (2019) Review of Ambient Monitoring Data from Three Sydney Road Tunnels (M5 East, Lane Cove, and Cross-City). Report for NSW Roads & Maritime Services on behalf of the Advisory Committee on Tunnel Air Quality.

Important disclaimer

Contents

Executive Summary

This study has analysed ambient monitoring data for 2009-2013 from sites near the M5 ventilation stack and for 2005-2006 from sites near the Cross City Tunnel (CCT) ventilation stack to address two questions:

(i) What is the potential for a measurable ambient air quality impact from the stack emissions?
(ii) Are any impacts from stack emissions discernible in the ambient monitoring data?

Potential for a measurable ambient air quality impact

The potential to detect a measurable air quality impact due to stack emissions is determined by:

1. The "noise" (typical local variability) in the ambient monitoring data. By comparing the hour-by-hour differences in concentrations between two closely spaced monitoring sites, the noise in the data for the various pollutants were determined to be (see also Table 13):
   - NO_2 – 2.0 µg/m^3 at M5 sites, 3.7 µg/m^3 at CCT sites
   - PM_{10} – 1.6 µg/m^3 at M5 sites, 2.5 µg/m^3 at CCT sites
   - CO – 0.08 ppm at M5 sites, 0.06 ppm at CCT sites.

   The data averaging used in the analysis reduced the "noise" by about a factor of 5 in the final results.
2. The size of the impact, i.e. the incremental increase in ground-level concentration due to the stack emissions, is also referred to as the "signal". To be detected, the "signal" must be sufficiently larger than the "noise" in the data. This value is generally not known a priori but is proportional to the emission rate of the pollutant. Thus the signal for a pollutant emitted at a higher rate will be larger than for a pollutant with a lower emission rate. These together with estimates for the noise can be used to compute the relative signal-to-noise ratios for each pollutant to determine which has the highest potential to be detected.
3. The monitoring site must be downwind of the stack. Including wind directions within ±10° of directly downwind from the stack, the proportion of hours when the M5 sites are downwind of the stack is: T1 21%, CBMS 5.3%, U1 2.7%, and X1 1.3%.
4. If multiple pollutants can be detected, the ratio of the measured non-reactive pollutants (after accounting for background pollutant levels) should be the same as their concentrations in the vent stack to confirm the stack as a likely source. Because this ratio is the same for emissions from vehicles using roads or the tunnel, this is not a unique identifier (i.e. it is a necessary but not sufficient condition that stack emissions are the source).

Is there a measurable impact of stack emissions?

The analysis used in this study is to calculate for each hour the deviation of the 1-hour average concentration at the monitoring site from that at OEH Earlwood. The effect of this is to remove region-wide variations in the pollutant concentrations to show the influence of more local sources and potentially an impact from the M5 stack. These deviations are averaged in 5° wind direction bins and plotted versus wind direction. An advantage of this technique over some other statistical methods is that it allows for the graphical presentation of results including as polar plots, which can be easily understood by informed members of the community.

The analysis demonstrated the presence of a measurable stack impact at CBMS but not at any other M5 sites (three of which are closer to the stack), nor at any of the CCT sites. At CBMS which is downwind from the M5 stack for a wind direction of 33°, the impact was detected in the NO_2 data as a 3 μg/m^3, which was significantly larger than the standard deviation of the noise of 0.5 μg/m^3. This peak was present in each of the 5 years of analysed data with some minor year-to-year differences. For reference, the NEPM standard for 1-hour average NO_2 concentrations is 246 μg/m^3.

Although the magnitude of the NO_2 peak is about 3 μg/m^3, it only contributes about 0.15 μg/m^3 to the overall annual average NO_2 concentration at the site. A context for these values is the observed increases in concentration by an average of 25 μg/m^3 at the near-motorway monitoring sites contributing to an increase of about 10 μg/m^3 in the annual averages. For reference, the NEPM standard for annual average NO_2 concentrations is 61.5 μg/m^3.

List of Figures

List of Tables

This page is intentionally blank

1 Introduction

1.1 Objective

The aim of the study is to analyse available NSW ambient and tunnel stack data to determine:

(i) What is the potential for a measurable ambient air quality impact from the stack emissions?
(ii) Are there any impacts from stack emissions discernible in the ambient monitoring data?

1.2 Background

This project has been delivered at the request of NSW Roads & Maritime Services on behalf of Advisory Committee on Tunnel Air Quality.

Community confidence in the protection of local ambient air quality is critical to the acceptance of road tunnels as an effective transport solution. This is particularly important for Sydney's WestConnex motorway projects, which will be the longest road tunnel network in Australia, comprising over 24 km of tunnels.

The M5 East (opened 2001) and Cross City tunnel (CCT, opened 2005) conducted ambient air quality monitoring to verify the performance of the stacks.

While this data has been analysed in a number of different ways in various reports, there is benefit in preparing a consolidated report analysing what the monitoring data can tell us about the ability of tunnel stacks to protect local air quality.

1.3 Scope of Work

This report provides an analysis of monitoring data around the M5 and Cross City Tunnel ventilation stacks to address the study objectives.

2 Data

This section describes the site locations (2.1), the monitoring data (2.2), the annual averaged air quality data (0), the wind data (2.4) and the stack emission data (2.5).

2.1 Site locations

The locations of the M5 stack and the four main monitoring sites are shown in Figure 1 along with the monitoring sites near the entrances to the tunnel – M1 at the eastern or Marsh St end and F1 at the western or Bexley Rd end. Also shown is the OEH Earlwood monitoring site, which was used as a reference site for background air quality data in this report's analysis. The coordinates and locations relative to the M5 stack are listed in Table 1. The stack emission parameters are listed in a later section in Table 9.

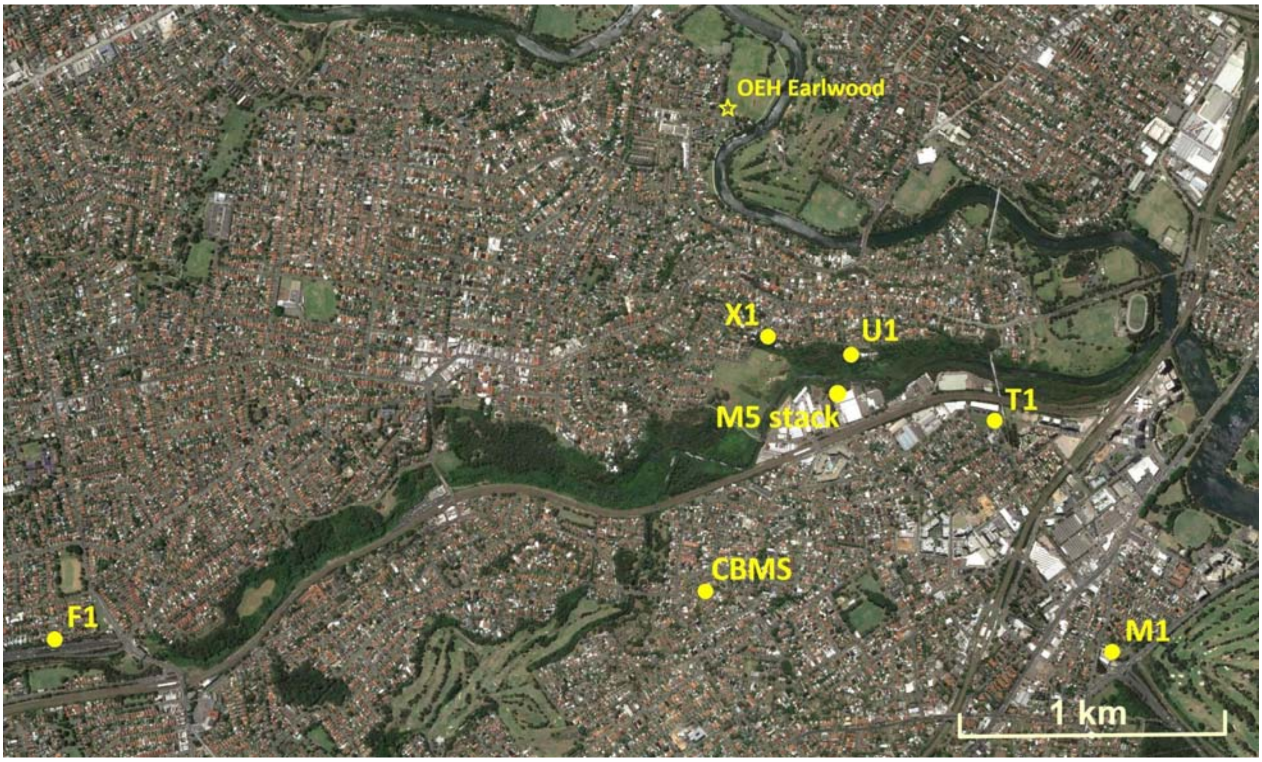


Figure 1 Map of the 6 monitoring sites around M5 stack and the OEH Earlwood site

Table 1. Locations of M5 monitoring sites

Monitoring site	AMG Easting [m]	AMG Northing [m]	Approx. elevation AHD [m]	Distance from M5 stack [m]	Wind direction when site directly downwind of stack
M5 Stack	328,212	6244,298	40 (stack top)		
CBMS	327,713	6243,517	30	927	33°
T1	328,820	6244,172	5	621	282°
U1	328,277	6244,422	25	140	208°
X1	327,923	6244,507	35	357	126°
F1	325,204	6243,339		3157	72°
M1	329,258	6243,283		1457	314°
OEH Earlwood	327,600	6245,400		1270	
OEH Chullora	319,300	6247,900		9600	

The locations of the Cross City Tunnel (CCT) vent stack and the four nearby monitoring sites are shown in Figure 2. The coordinates and locations relative to the CCT ventilation stack are listed in Table 2.

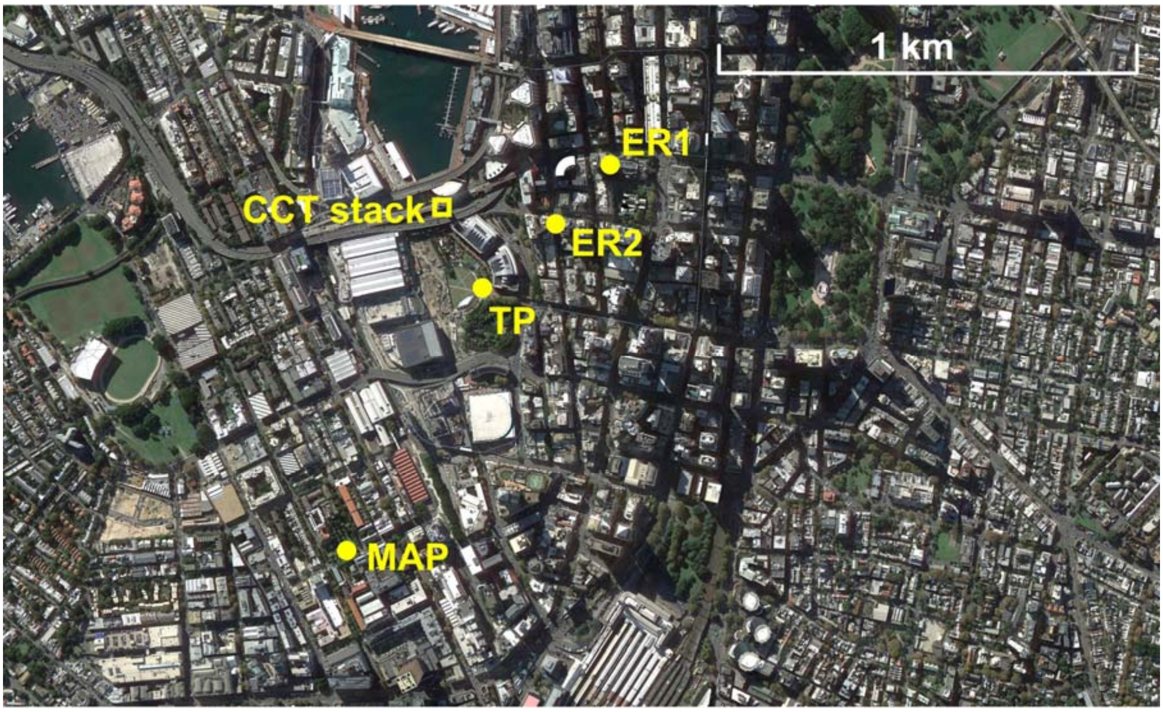


Figure 2 Map of the Cross City Tunnel monitoring sites around the CCT stack.

Table 2. Locations of CCT monitoring sites relative to CCT stack

Monitoring site	AMG Easting [m]	AMG Northing [m]	Distance from CCT stack [m]	Wind direction when site directly downwind of stack
CCT Stack	333,716	6250,363		
ER1 - Elevated Receptor 1	333,893	6250,327	181	282°
ER2 - Elevated Receptor 2	333,973	6250,447	270	252°
MAP - Mary Ann St Park	333,458	6249,564	840	18°
TP - Tumbalong Park	333,741	6250,181	184	352°
OEH Earlwood	327,600	6245,400	7900	
OEH Rozelle	330,000	6251,200	3800	

2.2 Site data

Available monitoring, meteorological and stack emission data was collated by RMS and ERM for the period from 2004 to 2017 and reported as 1-hour averages. Exceptional events were removed from the database. Exceptional events are those where the whole airshed is impacted by natural emission sources (i.e. bushfires, dust storms) or when a known highly localised emission source occurred near a monitoring location (i.e. controlled burn next to station). Not all parameters were measured for all years and there are significant gaps in the data as well as some issues with data quality; these data were flagged and not included in the analysis.

The most complete 5-year data set for the M5 monitoring sites was from 2009-2013, generally with greater than 90% data availability for all parameters. Table 3 lists the available parameters from each data set that were used in this report's analysis.

Monitoring data from the CCT sites (ER1, ER2, MAP, TP) was only available from September 2005 – June 2006 and Table 4 lists the available data used here.

Table 3. Pollutant and meteorological data availability for analysis around M5 stack for 2009-2013

Sites	CO	NO	NO_2	NOx	O_3	PM_{10}	$PM_{2.5}$	WD	WS
M5 stack	×	✓	✓	✓	×	✓	×	×	×
M5 monitoring sites									
CBMS	✓	×	✓	×	×	✓	×	✓	✓
F1	✓	×	✓	×	×	✓	×	✓	✓
M1	✓	×	✓	×	×	✓	×	✓	✓
T1	✓	×	✓	×	×	✓	×	✓	✓
U1	✓	×	✓	×	×	✓	×	✓	✓
X1	✓	×	✓	×	×	✓	×	✓	✓
OEH Earlwood	×	✓	✓	×	✓	✓	✓	✓	✓
OEH Chullora	✓	✓	✓	×	✓	✓	✓	✓	✓

Table 4. Pollutant and meteorological data availability for analysis around CCT stack for 2005-2006

Sites	CO	NO	NO_2	NOx	O_3	PM_{10}	$PM_{2.5}$	WD	WS
CCT stack	✓	×	×	✓	✓	✓	×	×	×
CCT monitoring sites									
ER1	✓	×	✓	×	×	✓	✓	×	×
ER2	✓	×	✓	×	×	✓	✓	×	×
MAP	✓	×	✓	×	×	✓	✓	×	×
TP	✓	×	✓	×	×	✓	✓	×	×
OEH Earlwood	×	✓	✓	×	✓	✓	✓	✓	✓
OEH Rozelle	✓	✓	✓	×	✓	✓	×	✓	✓

2.3 Annual-averaged air quality data

The annual averages for NO_2, CO and PM_{10} at the M5 monitoring sites and two OEH monitoring sites were compared for the years 2009-2013. The OEH Earlwood site, located about 1.3 km from the M5 stack, was used as the background sites for NO_2 and PM_{10} but it did not include CO measurements, so the OEH Chullora site which had CO data was used instead.

Table 5 lists the NO_2 averages showing small year-to-year variations. The averages were similar at the 4 main M5 monitoring site (CBMS, T1, U1, X1) and OEH Chullora at about 25 µg/m^3. These were about

5 μg/m^3 higher than at OEH Earlwood. In contrast, the F1 and M1 averages were highest at 33.3-38.7 μg/m^3; these are the sites near the M5 motorway.

It should be noted that the OEH monitors are sited to measure representative regional background. The differences between the averages at OEH sites indicate regional variations across the airshed. In contrast, the M5 and CCT monitoring sites are sited to detect possible impacts from the stacks and/or M5 motorway, they are not part of the OEH network.

Table 5. Annual average NO_2 concentrations at monitoring sites around M5 stack

Year	Annual average NO_2 [μg/m^3]							
	CBMS	T1	U1	X1	F1	M1	OEH Earlwood	OEH Chullora
2009	25.9	27.5	23.7	25.5	34.4	36.4	19.9	24.5
2010	24.8	27.1	25.1	24.5	33.7	38.3	20.1	24.4
2011	23.1	26.2	23.8	22.8	34.3	36.8	18.9	24.9
2012	23.0	22.4	24.1	24.5	33.3	38.7	18.1	25.5
2013	23.0	24.9	24.3	26.1	33.7	37.3	20.2	25.6
Average	***24.0***	***25.6***	***24.2***	***24.7***	***33.9***	***37.5***	***19.4***	***25.0***

Table 6 compares the PM_{10} averages and shows smaller differences between sites than for NO_2 but relatively larger year-to-year variations. The 5-year PM_{10} averages are generally similar at about 15 μg/m^3 at CBMS, U1 and X1, 1-2 μg/m^3 higher at T1 and F1, and about 19 μg/m^3 at M1 and the two OEH sites.

Table 6. Annual average PM_{10} concentrations at monitoring sites around M5 stack and background OEH sites

Year	Annual average PM_{10} [μg/m^3]							
	CBMS	T1	U1	X1	F1	M1	OEH Earlwood	OEH Chullora
2009	17.6	18.3	17.0	15.5	18.7	20.1	21.8	21.3
2010	15.2	16.1	14.5	12.8	17.3	18.2	17.9	17.7
2011	12.8	16.5	15.2	13.7	17.3	18.5	17.7	19.7
2012	15.4	16.2	15.3	15.4	17.3	19.7	19.6	18.1
2013	15.5	16.1	14.4	14.5	15.9	19.4	19.9	18.3
Average	***15.3***	***16.7***	***15.3***	***14.4***	***17.3***	***19.2***	***19.4***	***19.0***

For CO, Table 7 shows the averages are lowest at CBMS and U1, followed by X1 and T1. All these 4 sites have lower averages then OEH Chullora. The two sites F1 and M1 had the highest CO averages with the value at F1 almost double that at CBMS.

Table 7. Annual average CO concentrations at monitoring sites around M5 stack and background OEH site

Year	Annual average CO [ppm]						
	CBMS	T1	U1	X1	F1	M1	OEH Chullora
2009	0.25	0.33	0.26	0.27	0.48	0.41	0.31
2010	0.24	0.29	0.25	0.26	0.46	0.39	0.38
2011	0.19	0.32	0.22	0.29	0.42	0.34	0.36
2012	0.22	0.26	0.20	0.28	0.43	0.37	0.36
2013	0.21	0.26	0.21	0.22	0.39	0.33	0.33
Average	***0.22***	***0.29***	***0.23***	***0.27***	***0.43***	***0.37***	***0.35***

Table 8 lists averages for NO_2, CO, PM_{10} and $PM_{2.5}$ at the monitoring sites near the CCT stacks for the period September 2005 – June 2006. It includes averages for OEH Earlwood and Rozelle, the latter was used as the background site for CO. For the analysis in section 4, similar results were obtained using either Earlwood or Rozelle backgrounds for NO_2 and PM_{10}, so Earlwood data was used for greater consistency through the report.

The NO_2 averages at the CCT monitoring sites are 50-75% higher than the OEH sites with the highest values at the elevated receptors. The highest CO average is at TP with the other sites within 10% of OEH Rozelle. In contrast the PM_{10} and $PM_{2.5}$ averages at the CCT monitoring sites are the same or lower than at the OEH sites.

Table 8. Average concentrations at monitoring sites around CCT stack and background OEH sites

Pollutant	Average concentrations (Sep 2005 – June 2006)					
	ER1	ER2	MAP	TP	OEH Earlwood	OEH Rozelle
NO_2	41.1*	41.6	34.8	36.9	25.4	23.3
CO	0.24	0.25	0.20	0.30	-	0.22
PM_{10}	15.6	20.4	19.9	20.7	23.2	20.6
$PM_{2.5}$	6.2	6.4	6.2	6.4	6.4	-

*At ER1, NO_2 data only available Jan – Jun 2006

2.4 Wind data

The wind roses for the 4 monitoring sites closest to the M5 stack as well as OEH Earlwood for 2010 are compared in Figure 3. Their locations are shown in Figure 1. Not unexpectedly, all the wind roses show the same dominant wind directions (W, NE and SW) but with up to 10-20° differences between sites in the peak wind directions and marked differences in the wind speeds. For example, higher wind speeds are measured at CBMS and U1 than at T1 and Earlwood, probably because of their more exposed locations. The proportion of winds in the three dominant wind directions is similar across sites except at T1 where westerlies are more frequent.

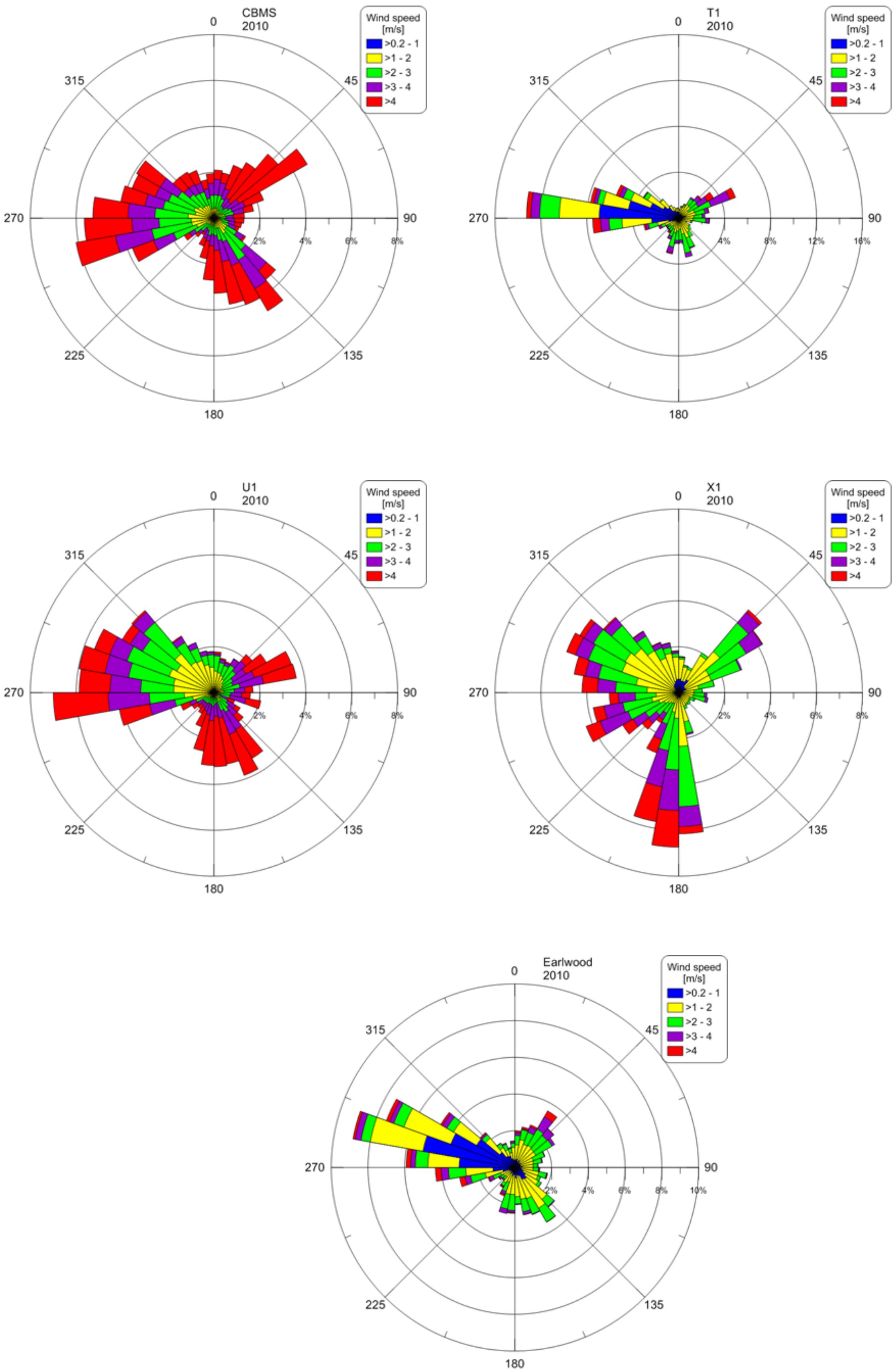


Figure 3 Wind roses for 2010 at four M5 monitoring sites and OEH Earlwood

Figure 4 shows the wind roses at the 2 monitoring sites (F1 and M1) close to the M5 motorway. These show the same general wind patterns as the other sites but with the dominant direction being WSW at F1 and NW at M1. These differences are possibly due the influence of local topographic features and less than ideal siting for measuring the regional flow.

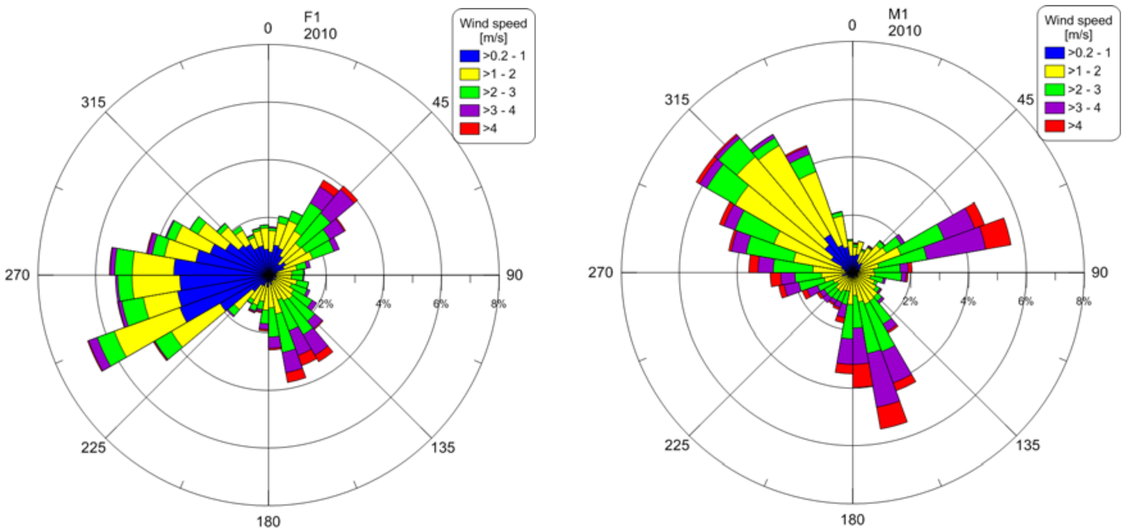


Figure 4 Wind roses for 2010 at the 2 monitoring sites near the M5 motorway – F1 and M1

A comparison of the frequency of the wind directions between the 7 sites is given in Figure 5. As discussed above, the biggest differences are the narrow distribution of westerly winds at T1, southerly winds at X1, and WSW winds at Earlwood. The differences at sites F1 and M1 are also marked.

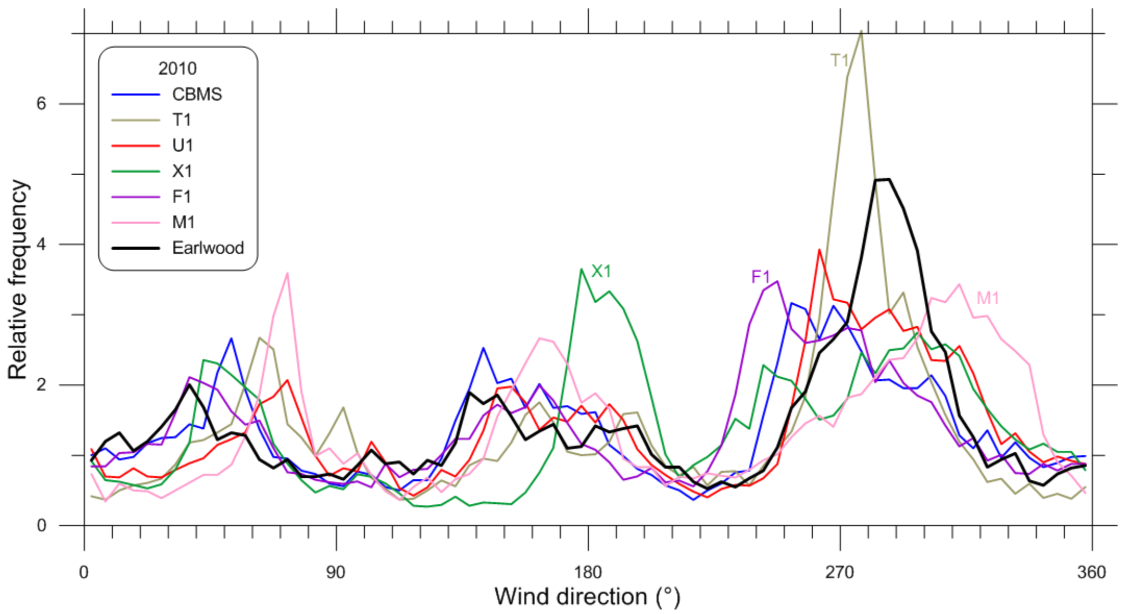


Figure 5 Comparison of 2010 wind direction distributions at the 6 M5 monitoring sites and OEH Earlwood

Despite the differences between the wind roses at the monitoring sites (Figure 3, Figure 4), an hour-by-hour comparison of wind directions between the sites shows generally good agreement. For example, the scatter plots in Figure 6 compare hour-by-hour wind directions at CBMS with those at Earlwood (left-hand panel) and U1 (right-hand panel) for 2010. Most hour-by-hour values agree within 10°; differences are most likely due to small variations across the airshed including the influence of local variations in topography and vegetation (e.g. Bureau of Meteorology, 1997). Given these small differences, it is assumed in the analysis in Sections 4and 5 that the hourly wind direction measured at each site is representative of winds between the M5 stack and that site.

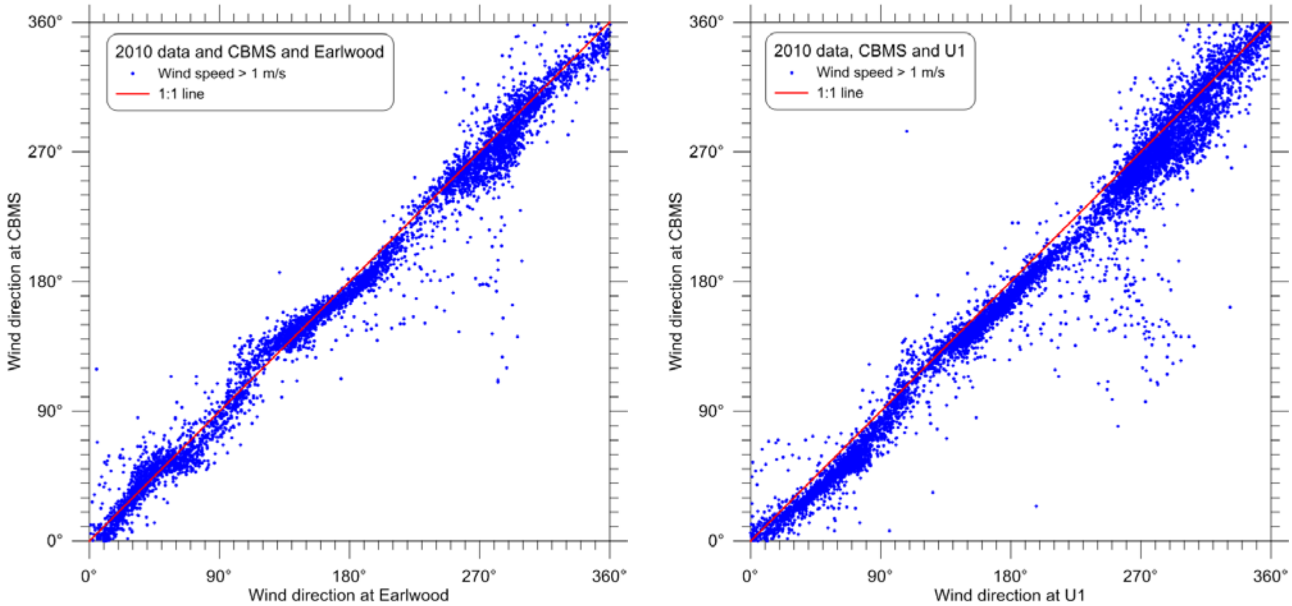


Figure 6 Scatter plots comparing wind directions hour-by-hour at CBMS with those at Earlwood (left-hand panel) and U1 (right-hand panel). Data for 2010 with wind speeds greater than 1 m/s (as used in Sections 4 and 5).

Figure 7 shows the data from CBMS for each of the years 2009 to 2013, indicating the small year-to-year variation in wind patterns. This shows the representativeness of 2010, which was selected as a single year for some of the analysis in section 4.

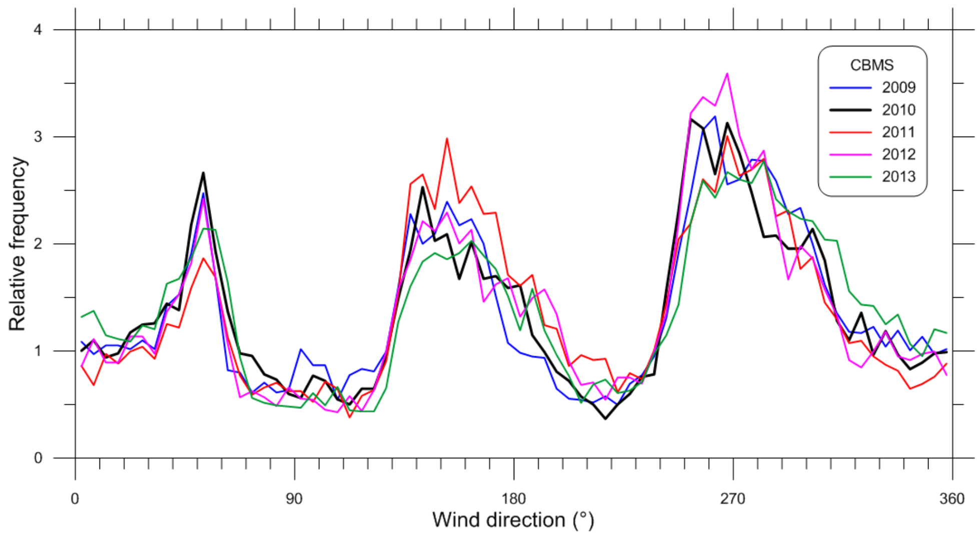


Figure 7 Comparison between annual wind direction distributions at CBMS for 5 years from 2009-2013

2.5 Stack emissions

For the purposes of this analysis, the relevant parameters from the stack emission data are both the absolute pollutant emission rates as well as the ratios between the emission rates. Table 9 lists representative values of the stack emission parameters in peak traffic conditions. Note that the NO_2/NOx ratio in the emissions is typically 0.11. The efflux temperature is generally 15-30°C. Modelled ground-level concentrations in the vicinity of the M5 stack are given in Section 3.2.

Table 9. Details of M5 and CCT ventilation stacks (typical maximum emission values)

Parameter	M5 stack	CCT stack
AMG Easting [m]		
AMG Northing [m]		
Stack height above ground level [m]	35	65
Effective stack diameter [m]	7.3	6.2
Efflux velocity [m/s]	20	20
Volume flow rate [m^3/s]	840	600
NO_x emission rate [g/s]	~10	~2.0
CO emission rate [g/s]	~30	~5
PM_{10} emission rate [g/s]	~0.6	~0.07

For non-reactive pollutants from a given source, the ratios between the pollutant concentrations remain constant as the plume dilutes, so the ratios can be used to distinguish between different sources. A difficulty with ratios involving NO_2 is that NO can react chemically with ozone to produce NO_2 as the plume disperses. Ideally it would be better to use NOx concentrations as NOx (sum of NO + NO_2) is conserved, but the ambient monitoring data at most of the sites considered here do not include NOx measurements, so that we are limited to considering NO_2.

The correlation between the hourly emission rates of the pollutants listed in Table 3 were determined using scatter plots to help identify data quality issues. The quality of the data from the M5 stack was generally poor (variable baseline, inexplicable changes in scale) so that it was only possible to determine the PM_{10}/NO_2 ratio via the PM_{10}/NO ratio determined from the scatter plots and assuming the same NO_2/NO_x ratio as for the other stacks.

Table 10. Ratios of stack pollutant mass emission rates

Stack	Ratio of stack pollutant mass emission rates			
	CO/NO_2	PM_{10}/NO_2	CO/PM_{10}	NO_2/NOx
M5	-	0.5	-	-
CCT	22	0.39	56	0.11
LCT Sirius	25	0.42	60	0.11
LCT Marden (see text)	*11**	*0.20**	55	0.12
Estimate for M5	**25**	**0.5**		**0.11**

Table 10 lists the CO/NO_2, PM_{10}/NO_2, CO/PM_{10}, and NO_2/NO_x ratios that could be determined from all 4 stacks. The time range of the data used was 2009-2013 for the M5 stack, 2016-2017 for the CCT stack, and 2015-2016 for the Lane Cove Tunnel (LCT) stacks. The data from LCT Marden appears anomalous with both CO/NO_2 and PM_{10}/NO_2 lower than the other stacks by a factor of 2, but similar values for CO/PM_{10} and NO_2/NOx as the other stacks. This could be explained by a factor of 2 error in the calibration of the NOx equipment at LCT Marden but there may be other reasons; these have not been investigated further here.

Based on the values in Table 10, the best estimates for the ratios of mass emission rates for pollutants from the M5 stack were determined to be $CO:NO_x:NO_2:PM_{10}$ = 50:18:2:1.

3 Potential to detect an impact

The potential to detect a measurable ambient air quality impact due to emissions from a tunnel vent stack is influenced by the following factors:

- The size of the "signal" (i.e. the ground-level concentration due to stack emissions) and the typical variability or "noise" in the monitoring data. How much hour-to-hour and site-to-site variability is there in the ambient air quality? For an impact to be measurable it must stand out from this normal variability. In other words, the "signal" must stand out from the "noise" in the data. [*This concept of detecting a "signal" in the "noise" can be explained using the analogy of a conversation in a restaurant. If the restaurant is very noisy and the person you're talking to is speaking softly (a small "signal"), then you won't be able to understand what they're saying. Because the "noise" is high, they need to speak loudly (big "signal") for you to understand them. On the other hand, in a quiet restaurant (low "noise"), then you'll be able to understand them even if they speak quite softly (small "signal").*]
- Is any particular pollutant more likely to be detected than any others?
- What are the most appropriate data analysis techniques? What other information is needed to identify the source of a signal?

3.1 How "noisy" is the data?

The time series of the concentration of a common urban air pollutant such as NO_2, CO or PM_{10} varies from hour to hour due to the many sources of air pollution in a region and the various time scales of the turbulence (mixing and dilution processes) in the atmosphere. Figure 8 is an example of the variation in NO_2 measured at two of the M5 sites for a week in February 2010. It shows strong diurnal as well as day-to-day variations.

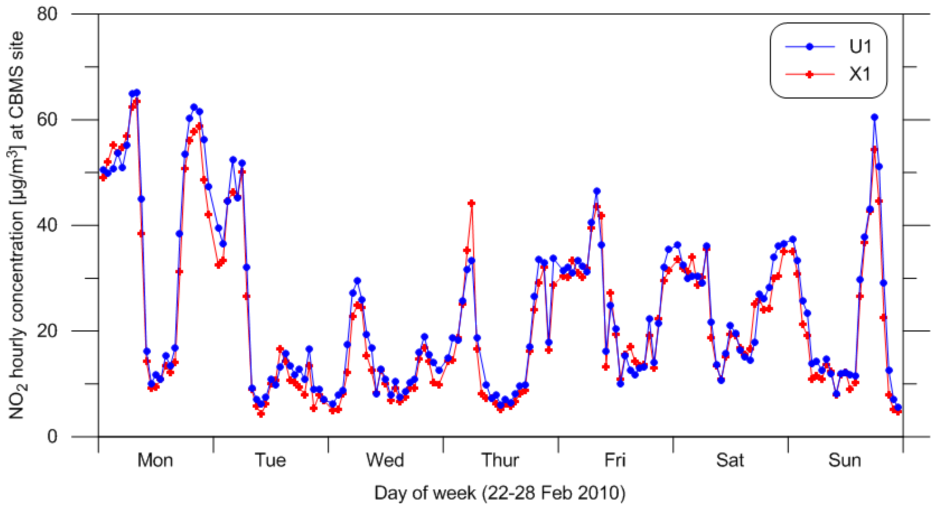


Figure 8 Typical hourly variation in NO_2 at two M5 monitoring sites

In 2010 at these two sites (U1 and X1), the highest NO_2 concentration was 109 µg/m^3 and the 99th percentile value was 71 µg/m^3. Thus if there was just a single monitoring site, then for a measurable impact from a source to stand out from this natural variability without other information to identify the source, the signal would have to be very large, say about 100 µg/m^3 for NO_2.

However, Figure 8 shows that the concentrations at the two sites track each other quite closely, so that a given signal would stand out more clearly by analysing the differences in concentrations between the two sites. More generally, if there is a nearby background air quality site (not affected by local emissions), then we can calculate differences from it to remove larger scale regional variations including (most of) the diurnal cycle.

The typical “noise” in this difference was determined by analysis of the data in Figure 9, which shows the time series of hourly difference in NO_2 concentrations between the U1 and X1 sites during 2010. The distance between these sites is only 360 m, so that regional effects should be the same at both sites and hence be cancelled out. The remaining scatter represents the typical local variability. The right-hand panel of Figure 9 shows a Gaussian fit to the corresponding probability distribution with a standard deviation of 2.0 µg/m^3. The tails are wider than a Gaussian so that instead of a 3σ range, we also compute the range that is only exceeded by 1% of values. This is ±10 µg/m^3. Similar analysis of the U1-X1 differences for PM_{10} and CO resulted in the representative values for “noise” listed in Table 11.

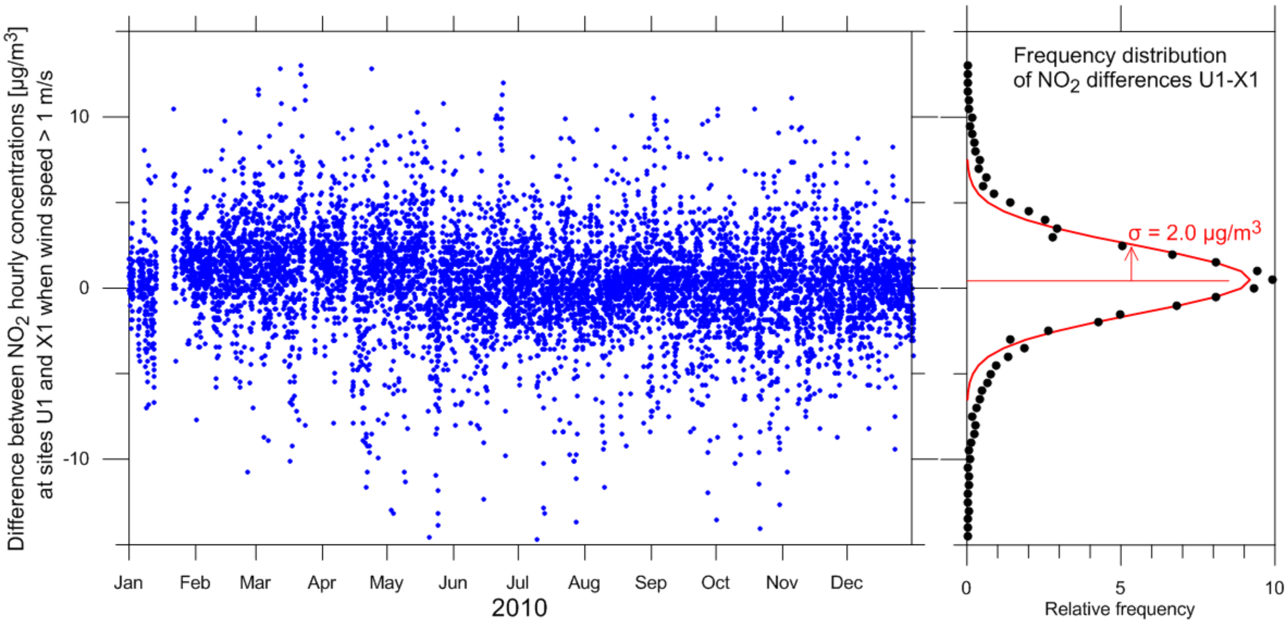


Figure 9 Typical variation in NO_2 between M5 monitoring sites, as shown by difference in hourly NO_2 concentrations measured at U1 and X1 sites during 2010.

Table 11. Typical site-to-site variation ("noise") in hourly concentration measurements at M5 monitoring sites

Pollutant	Standard deviation (σ)	99% of data within this range
NO_2	2.0 µg/m^3	±10.0 µg/m^3
PM_{10}	1.6 µg/m^3	±8.5 µg/m^3
CO	0.08 ppm	±0.50 ppm

The results in the right-hand column of Table 11 indicate the magnitude of a single 1-hour event needed for it to stand out from the noise. The analysis in the following Section 4 shows that by averaging over a longer period, it is possible to identify a signal in CO with a magnitude of about 0.5σ, i.e. half the values listed in the middle column of Table 11.

3.2 What is the possible size of a "signal"?

Previous dispersion modelling for the M5 stack (Hibberd, 2006) provided predictions of maximum 1-hour average ground-level concentrations for NOx. Scaling these results to the emission rates in Table 9 and assuming a NO_2/NOx emission ratio of 0.11, the likely maximum 1-hour average concentrations in the vicinity of the monitoring sites are:

- 2.5 µg/m^3 for NO_2
- 0.05 ppm (68 µg/m^3) for CO
- 1.4 µg/m^3 for PM_{10}.

This ignores conversion of NO emitted from the stack to NO_2 in the presence of ozone as the plume mixes with the ambient air, which would lead to greater NO_2 concentrations than estimated above (e.g. NSW EPA, 2015). Apart from NO_2, these values are close to the typical uncertainty in ambient air quality measurements (1 µg/m^3 for NO_2, 0.05 ppm for CO, 1 µg/m^3 for PM_{10}). This indicates that any change in CO or PM_{10} due to stack emissions is probably undetectable in any single hourly measurement, but it might be possible using data averaging techniques.

3.3 What pollutant is most likely to be detected?

The principles of dispersion of pollutants from a stack mean that the ratio of ground-level concentrations of non-reactive pollutants emitted by the stack is the same as the ratio of the concentrations of these pollutants in the stack, after accounting for background levels in the ambient air. Using the "noise" estimates in Table 11, we can calculate the relative signal-to-noise ratios for the various pollutants and hence determine which is the most likely of them to be able to be detected.

The estimated ratio of pollutant emission rates of CO:NO_2:PM_{10} for the M5 stack was determined (Table 10) to be 50:2:1. Neglecting for the moment the potential of conversion of NO to NO_2, this 50:2:1 would be the ratio of the ground-level concentrations of these pollutants. We can use these numerical values for a hypothetical incremental "signal" above background levels, i.e. a CO signal of 50 µg/m^3 (= 0.04 ppm), an NO_2 signal of 2 µg/m^3, and a PM_{10} signal of 1 µg/m^3. These are close to the maximum ground-level concentration given in the previous section. Comparing these with the respective estimates for noise give the signal-to-noise ratios listed in Table 12. This shows that the signal-to-noise ratios for PM_{10} and CO are about half that for NO_2. That is, if there is a measurable ambient air quality impact due to emissions from the M5 tunnel vent stack, it is most likely to be found by analysing the ambient NO_2 data. Note however that a signal to noise ratio of at least 3 is generally needed to have confidence that it is a true signal.

Table 12. Signal-to-noise ratios for a hypothetical "signal" (see text)

Pollutant	"Noise"	Hypothetical "signal"	Signal to noise ratio
NO_2	2.0 µg/m^3	2 µg/m^3	1.0
PM_{10}	1.6 µg/m^3	1 µg/m^3	0.63
CO	0.08 ppm	0.04 ppm	0.5

In practice, the signal-to-noise ratio for a NO_2 signal could be more than twice that for PM_{10} and CO because of the conversion of NO to NO_2. The stack emission rate of NO (expressed as NO_2) is about 8 times larger than that of NO_2 ($NO_2/NO_x \approx 0.11$), and the NO can react with available ozone to form more NO_2 than accounted for in the Table 12.

For the CCT and LCT Sirius stack, the signal-to-noise ratios for a hypothetical signal would be almost the same as in Table 12, just the signal-to-noise ratio for PM_{10} would be slightly lower at 0.5.

3.4 What are the most appropriate data analysis techniques?

For emissions from a tunnel vent stack to be detected at an ambient air quality monitoring site:

1. the monitoring site must be downwind of the vent stack
2. there must be a detectable increase in the concentration at the monitoring site (of a pollutant emitted by the vent stack) above what the concentration would have been if the vent stack wasn't present
3. it is probably necessary to use a data aggregation or data averaging technique because the magnitude of any signal is likely to be too small to detect in any single hourly measurement (signal magnitude similar to measurement uncertainty)
4. if multiple pollutants are detected, their concentrations (after accounting for background pollutant levels) should be in the same ratio as their concentrations in the vent stack (for non-reactive pollutants). Because this ratio is the same for emissions from vehicles using other roads, it is not a unique identifier (i.e. it is a necessary but not sufficient condition that stack emissions are the source.)

Because this issue is a community concern, an additional factor is that the analysis should be able to be understood as easily as possible by informed members of the community.

In brief, the method used here is to plot the concentration data versus wind direction to determine whether the concentrations are elevated when the vent stack is upwind of the monitoring site. The method is a type of back trajectory analysis and is described in more detail in the following section.

More generally, if a "signal" is detected at more than one monitoring site, the directions can be used to triangulate the location of the source (e.g. Rheingrover & Gordon, 1988). If elevated concentrations are observed at all sites for a particular wind direction, this indicates a more distant source that is upwind of all sites.

4 Is there a measurable impact near the M5 stack?

The analysis used here is to calculate for each hour the deviation (difference) of the 1-hour average concentration at the monitoring site from that at OEH Earlwood; this site is taken to represent the regional background concentration. We use the term "deviation" to refer to the differences from this regional background concentration, which is considered to be our reference level. The effect of this is to remove region-wide variations in the pollutant concentrations to show the influence of more local sources and potentially an impact from the M5 stack.

These deviations are plotted versus wind direction as scatter plots. These plots include the averages calculated in 5° wind direction bins. Peaks in the plot indicate a source upwind of the monitoring site at the corresponding wind direction angle. Polar plots of the average differences versus wind direction are also shown to assist in identifying potential sources. (Note that because of the complexity of pollution processes across a region, deviations can be negative as well as positive.)

Data are only included when the minimum wind speed criterion of 1 m/s is exceeded. Below this speed, the wind direction tends to be highly variable, so that it is not possible to assume straight-line back trajectories from the monitoring site to the source. A sensitivity analysis on the minimum wind speed found that increasing it to 2 or 3 m/s did not materially affect the results or change the conclusions from the analysis in this section. The scatter plot data are only shown for 2010 but very similar results were obtained for the other years in the period analysed from 2009-2013.

4.1 NO_2 at M5 monitoring sites

The first analysis shows scatter plots of the hourly deviations of the NO_2 concentrations at each M5 monitoring site from the background NO_2 concentration at the OEH Earlwood monitoring site. These are plotted versus wind direction, i.e. the angle (measured clockwise from north) that the wind is blowing from. Figure 10 shows the results for CBMS, which we'll discuss first. Plots for the other sites are in Figure 11 to Figure 15.

A black horizontal line at 5 µg/m^3 is the approximate average deviation from the NO_2 concentration at OEH Earlwood for the 4 sites CBMS, T1, U1 and X1. This deviation was identified earlier for the averages listed in Table 5. Each blue dot is a value for one hour in 2010 when there was valid data – a total of over 5000 points. The red line smooths the data by showing the average deviation versus wind direction.

There is a large scatter in the data points with values up to 30 µg/m^3 above and below the average. There are more points for wind directions near the dominant directions of NE, SE and W but there are generally sufficient points to reliably show any trends. The overall standard deviation of the points (σ = 7.5 µg/m^3) is much larger than in Figure 9 for the U1-X1 differences (2.1 µg/m^3). This is because the scatter in Figure 10 includes the variation in air quality between OEH Earlwood and the M5 monitoring site, whereas Figure 9 was just the inter-site variation between two M5 sites. The higher annual average NO_2 at the M5 sites compared to OEH Earlwood indicates the presence of local sources.

The arrow on the x-axis denotes the wind direction when the M5 stack is upwind of the specific monitoring site. There are no obvious distinguishing features in the data points around this wind direction of 33° in Figure 10, such as unusually high values compared to other wind directions. However, there is a small localised increase in the average of about 3 µg/m^3 for wind directions from 20-40°, which could be an impact due to stack emissions. This 3 µg/m^3 increase is smaller than other variations such as an increase of about 5 µg/m^3 above the overall average for easterlies (70-120°) and a decrease of about 5 µg/m^3 for southerlies (130-250°). The issue of whether or not a stack impact is present is discussed more fully after presenting the results for the other sites.

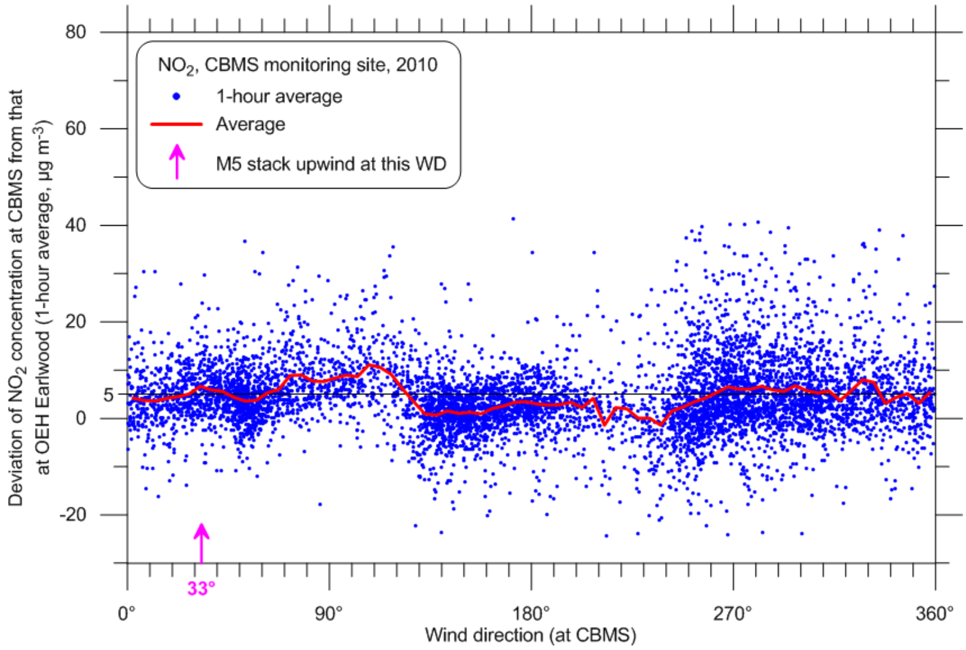


Figure 10 NO_2 deviations at CBMS vs wind direction for 2010

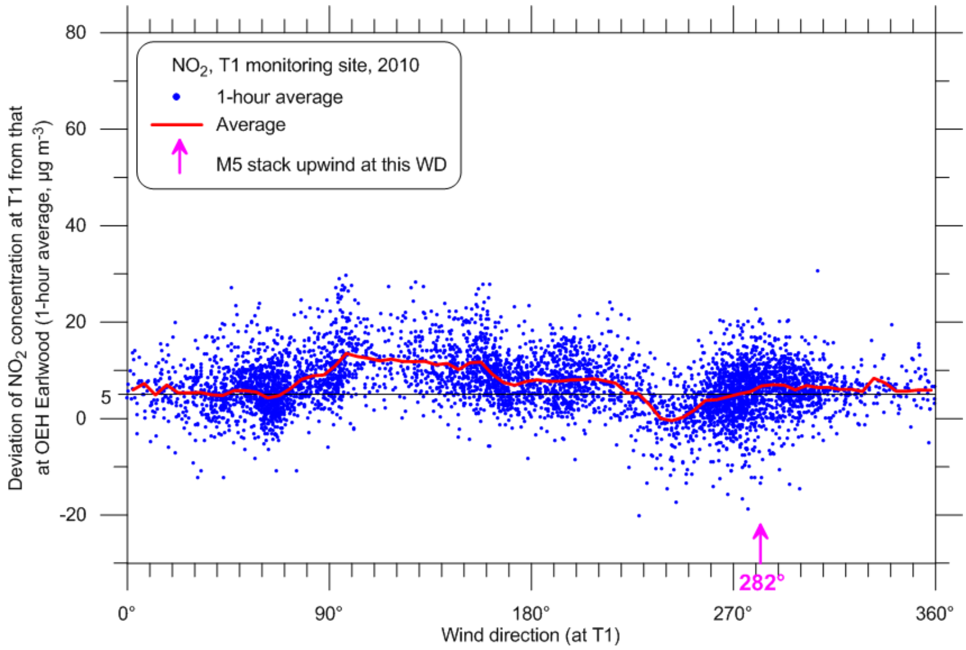


Figure 11 NO_2 deviations at T1 vs wind direction for 2010

Figure 11 for site T1 shows slightly less scatter in the data points (σ = 5.9 µg/m^3) than at CBMS but the average shows a larger increase above the overall average for south-easterlies (100-160°) and a minimum at 240°. There is no peak at the direction when the stack is upwind (282°); this direction is at the left-hand end of a plateau of values at about 6.5 µg/m^3.

The characteristics of the NO_2 deviations at U1 (Figure 12) and X1 (Figure 13) are quite similar to each other with no detectable features at the respective stack angles.

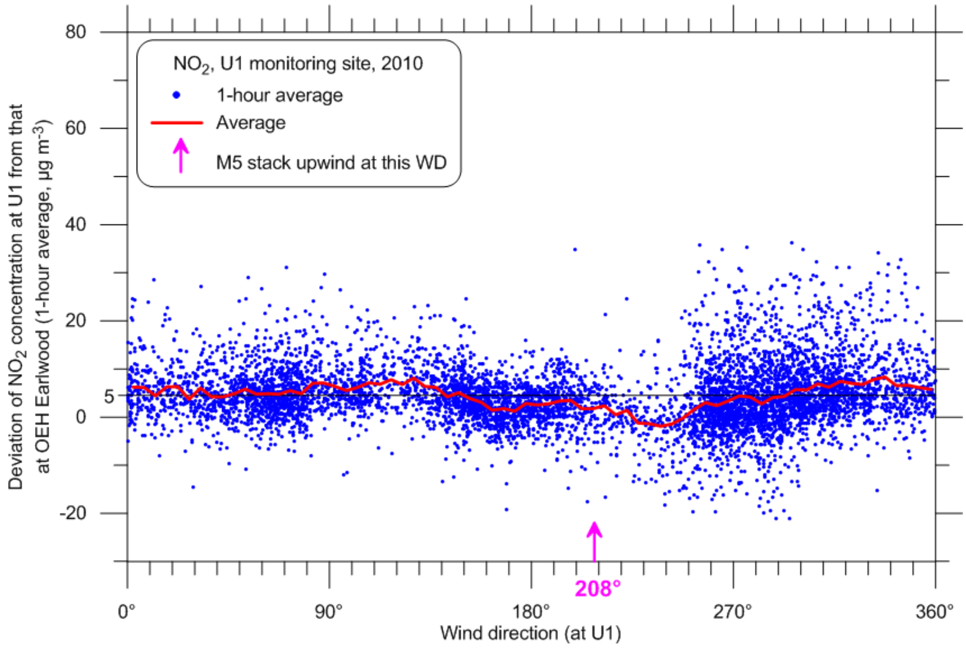


Figure 12 NO_2 deviations at U1 vs wind direction for 2010

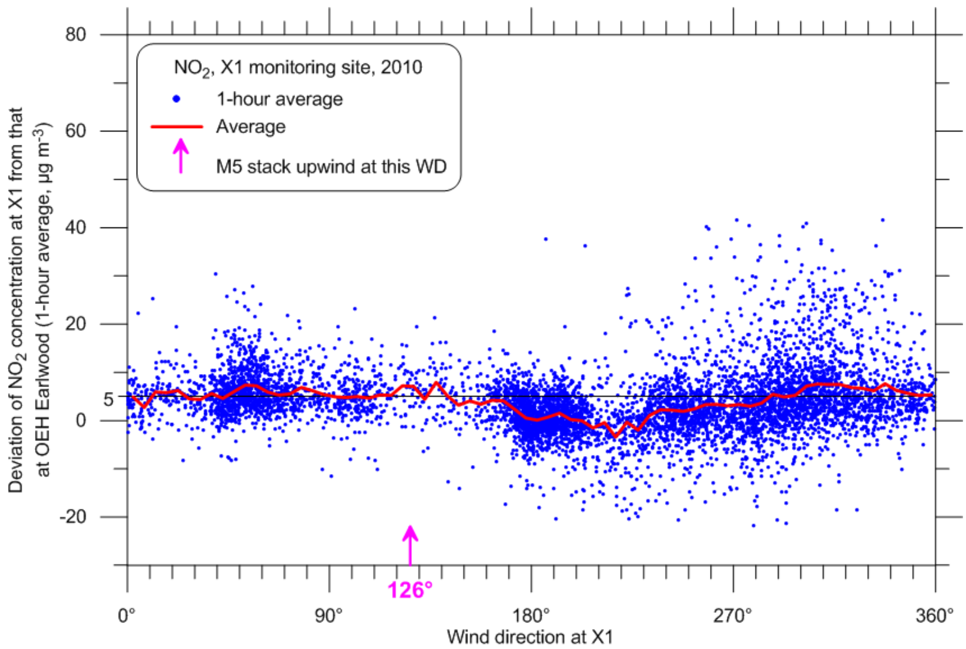


Figure 13 NO_2 deviations at X1 vs wind direction for 2010

In contrast to the above 4 sites, the deviations at the F1 and M1 sites near the motorway show a strong signal when the wind is blowing from the roads towards the sites. There is no discernible stack influence at either site. Site F1 (Figure 14) is located west of Bexley Road and just north of the motorway, which runs approximately east-west at this location (see also Figure 22). For winds in the southerly sector (110-250°), the average deviation above OEH Earwood is about 25 µg/m^3 whereas for winds in the northerly sector (270-45°), the deviations are similar to the average of 5 µg/m^3 at the four main M5 sites. It appears that emissions from vehicles on the motorway are responsible for these elevated levels.

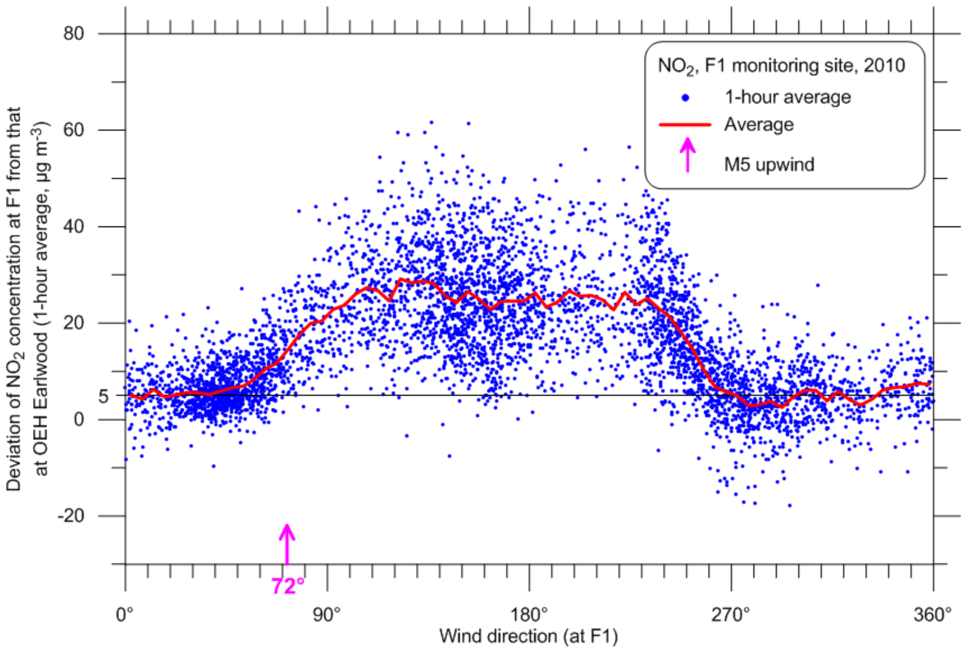


Figure 14 NO_2 deviations at F1 vs wind direction for 2010

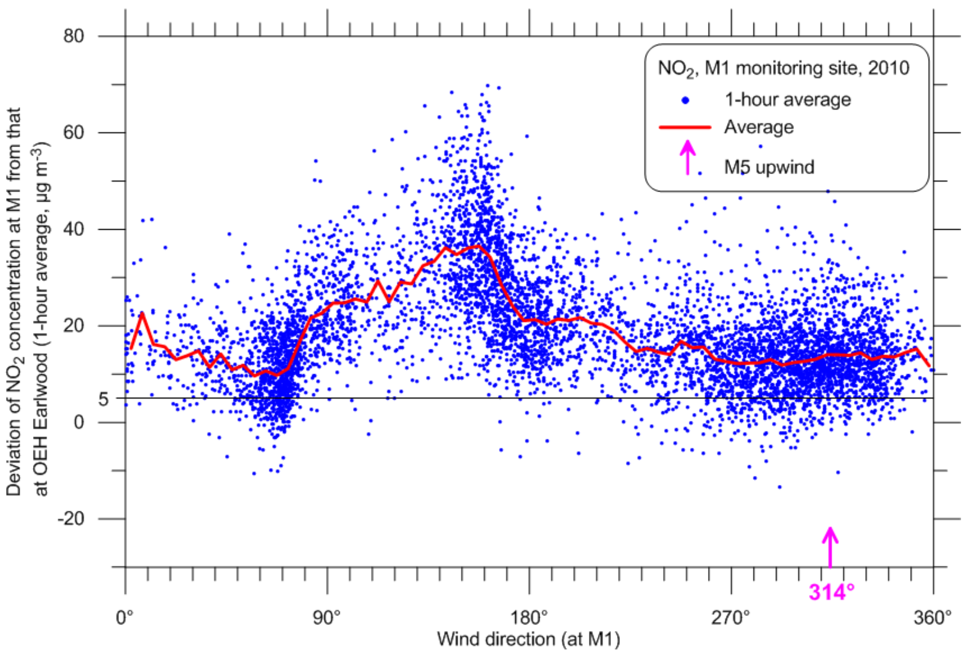


Figure 15 NO_2 deviations at M1 vs wind direction for 2010

At site M1 (Figure 15), located near Marsh Street and not far from the eastern entrance to the M5 tunnel, the average is elevated at all wind directions compared to the average at the four main M5 sites. The largest deviations of 35 µg/m^3 occur for winds at 155° winds (SSE), for which the major M5/Marsh St intersection is immediately upwind of the site, indicating this as a major source.

In order to compare the average curves from the 6 sites to identify common trends and differences, the averages are plotted in Figure 16, here for the five years 2009-2013. As identified above, the only site showing a potential stack signal is CBMS. It should be noted that the proportion of the year when the monitoring site is downwind of the stack could also affect the potential to detect a signal. Including wind directions within ±10° of directly downwind from the stack, the CBMS site is downwind 5.3% of the time compared to 21% for T1. In contrast, U1 is only downwind 2.7% of the time and X1 downwind 1.3% of the time.

Noteworthy is also the close agreement between the 5 sites CBMS, T1, U1, X1 and F1 for north-west to north-easterly winds with an average close to 5 µg/m^3 above OEH Earlwood. On the other hand, there are significant differences in the curves for winds with a southerly component. For the 4 main M5 sites (CMBS, T1, U1, X1) the largest difference is about 10 µg/m^3 between CBMS and T1 for south-easterly winds.

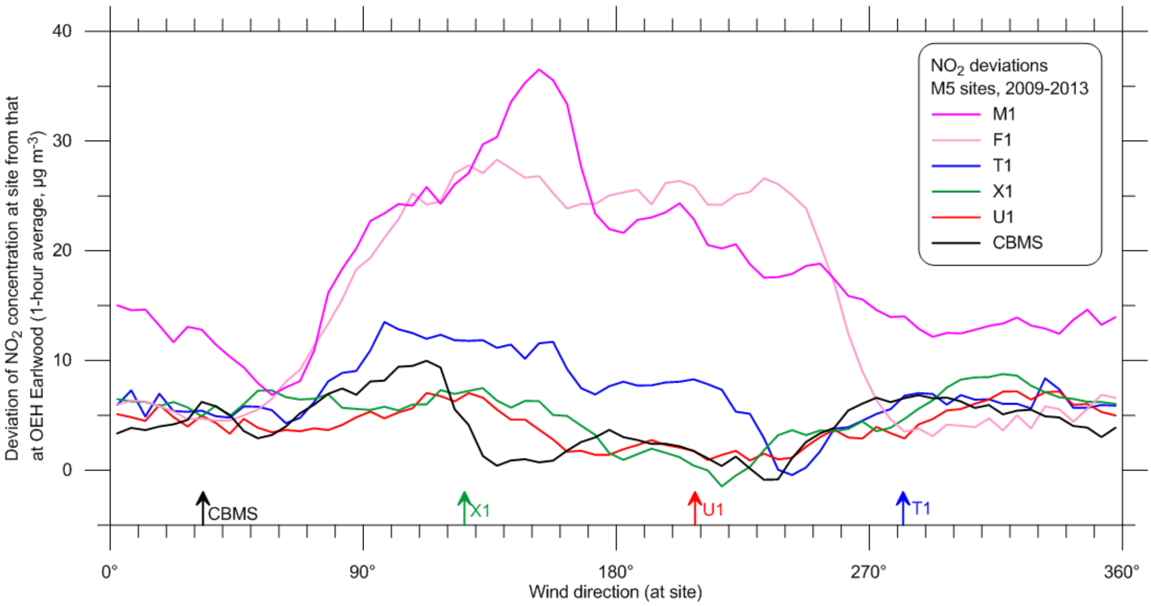


Figure 16 Average NO_2 deviations at all 6 sites vs wind direction for 2009-2013

An alternative graphical presentation of these results is using polar plots overlaid on a map of the region. The following explains the information in a polar pollution plot using the example in Figure 17.

- The green circle is centred on the monitoring site with north-south and east-west lines. The radius of the circle provides the scale and indicates an incremental NO_2 concentration (above that at OEH Earlwood) of 5 µg m^{-3}. At the F1 and M1 sites, there is an additional circle at 10 µg m^{-3}.
- The distance of the yellow line from the centre represents the incremental NO_2 concentration when the wind blows from that direction. In Figure 17, the NO_2 increment is about 5 µg m^{-3} for a NE wind, 10-12 µg m^{-3} for a SE wind, and close to zero for a WSW wind.

- Note that the position of the yellow line on the underlying map (such as next to a road, house or factory) does not indicate that this is the source of the pollutant. It is the direction from that point towards the monitoring site that is the wind direction for the corresponding incremental NO_2 concentration.
- The white line is the wind direction when the M5 stack is directly upwind of the site. In this example, the incremental NO_2 concentration for this wind direction is about 6 µg m^{-3}.

Figure 17 Example of polar plot. See text for explanation

Figure 18 shows the polar plots at all sites overlaid on a map of the region. It contains the same information as Figure 16 but in a different format. The large deviations at F1 and M1 for winds from the major roads and motorway stand out. With the focus here on the potential impact of M5 stack emissions, an enlargement of the figure showing the sites closest to the stack is given in Figure 19.

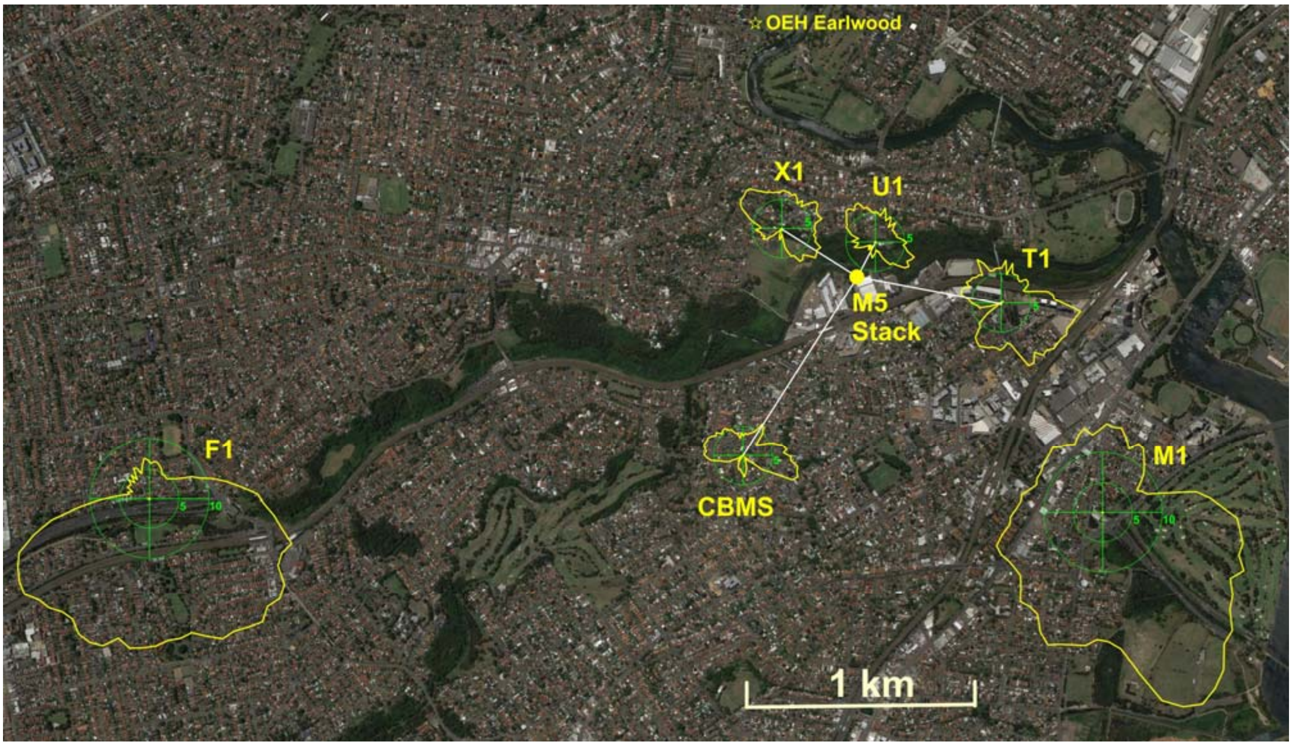


Figure 18 Polar plots of NO_2 deviations at 6 sites on map of area around M5 stack

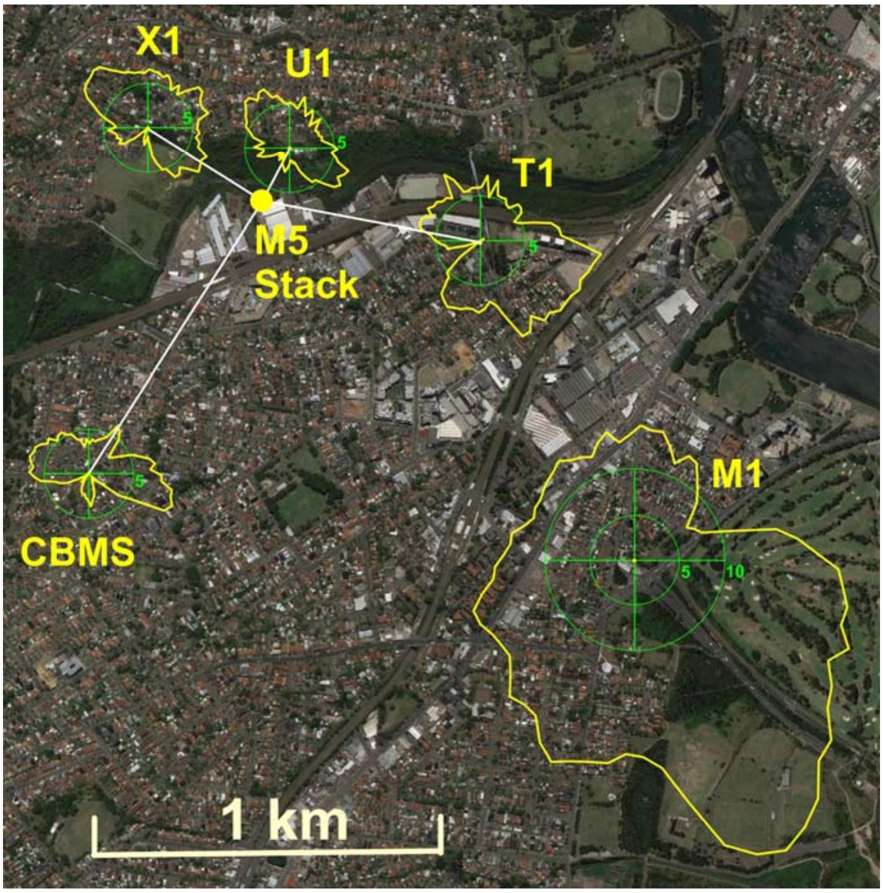


Figure 19 Polar plots of NO_2 deviations at sites near the M5 stack overlaid on map of the area

Figure 19 shows the small peak at CBMS of about 3 µg/m^3 in the NO_2 increment for winds blowing from the stack. The polar plots confirm that there aren't similar distinctive peaks at the other sites for winds blowing from the stack.

At CBMS, other than the peak at 33°, the most significant high concentration deviations are the broader peaks for ESE and WNW winds. Very similar broad peaks are also present in the polar plots at X1 and U1, the sites closest to each other, although the wind directions at which they occur are rotated slightly from those at CBMS to be SE and NW. The lowest concentrations at X1 and U1 are for winds from the south-westerly quadrant. At T1, the highest concentrations are for winds in the south-easterly quadrant. As discussed earlier, the concentration deviations are much higher at M1 for all wind directions with the maximum of 35 µg/m^3 for winds from the SSE

The similarities between the broad SE and NW peaks at T1, U1 and X1 (and rotated slightly anti-clockwise at CBMS) indicate that the main NO_2 sources for these lie further afield than the region encompassed by the main M5 monitoring sites and that they are area sources rather than a single point source. While the scope of this study does not extend to investigating these sources, a simple back trajectory analysis from the SE and ESE peaks at CBMS, X1 and U1 triangulates to sources in the vicinity of Sydney airport, with the port further upwind. The polar plots at T1 and M1 are consistent with this but their broader peaks indicate the presence of other sources, for example at M1 the M5/Marsh St intersection at 155°. Further investigation would be needed to be explain all the features of the polar plots.

We return to a discussion of the significance of the 3 µg/m^3 CBMS peak in Section 4.4.

4.2 CO and PM_{10} at M5 monitoring sites

Similar scatter plots as for NO_2 were analysed for CO and PM_{10}. Note that the CO data was compared to OEH Chullora to calculate the deviations because CO measurements were not available from OEH Earlwood. The detailed scatter plots at each site are included in the appendix (section 8) with Figure 29 to Figure 34 for CO and Figure 35 to Figure 40 for PM_{10}. Here we just present the summary plots of average deviations in Figure 20 and Figure 21.

Based on the relative signal-to-noise ratios in Table 12 for a given stack signal, one would expect it would be more difficult to detect a signal for CO or PM_{10} than for NO_2. The only suggestion of an M5 stack impact is in Figure 16 for the CO deviations at CBMS at wind directions near 33° with an increase of about 0.03 ppm for winds from 20-50°. However, care is need in interpreting this as a true signal given similar sized features at other sites in this wind direction range, where the stack is not directly upwind. For example, there is a small increase at X1 at 35°, a similar sized dip at U1 centred on 30° and a larger dip of 0.1 ppm at T1 centred on 35°.

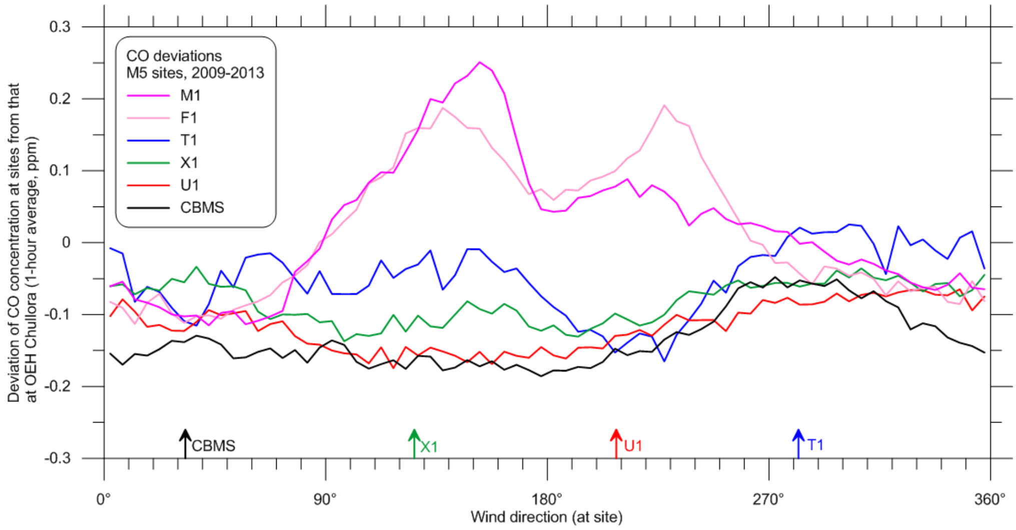


Figure 20 Average CO deviations at all 6 M5 sites vs wind direction for 2009-2013

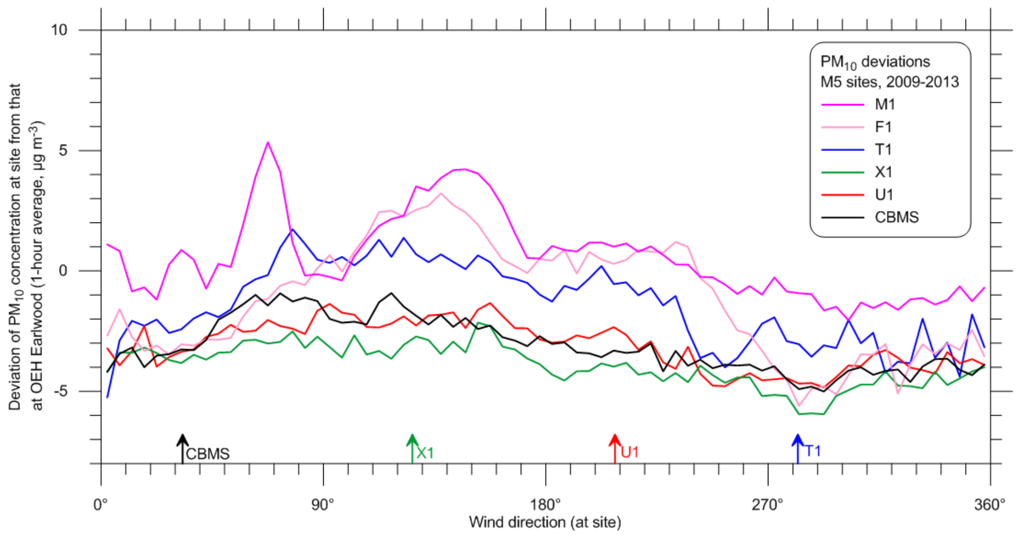


Figure 21 Average PM_{10} deviations at all 6 M5 sites vs wind direction for 2009-2013

Figure 21 shows the PM_{10} deviation curves. Given the size of fluctuations in the curves, there are no detectable stack signals at any of the sites. However, as for NO_2 and CO there are elevated levels for wind in the south-easterly and south-westerly quadrants at site F1 by about 5 µg/m^3 as well as at T1 by about 3 µg/m^3. The curve for M1 lies above the other curves for almost all wind directions with levels elevated by about 5 µg/m^3 in the ENE and SE peaks.

4.3 Pollutant ratios at F1 (near motorway)

Figure 16, Figure 20 and to a lesser extent Figure 21 show that the near-motorway site F1 has consistently higher levels of all three pollutants for southerly winds (135°-225°) compared to northerly winds (315°-45°). This provides the opportunity to compute the pollutant ratios at F1 for the motorway emissions. The polar plot of NO_2 deviations at F1 in Figure 22 shows the proximity of F1 to the motorway.

Figure 22 Polar plot of NO_2 deviations at F1 showing the proximity of the site to the motorway

Figure 23 shows the deviations at F1 for each of the 5 years as well as the 5-year averages. In this case, the deviations at F1 are from the values at U1 rather than OEH Earlwood in order to provide a more consistent baseline by using a more representative value for the local region (see Figure 16 to Figure 21). To assist in estimating the differences between pollutant levels for southerly and northerly winds, an offset has been applied to each curve to set the average deviation to zero for winds in the northerly quadrant (315° to 45°).

The NO_2 curves show the least point-to-point scatter and least year-to-year variability with increased scatter for CO and most scatter for PM_{10}. There are also some differences in the shapes of the curves. There are bumps in CO and PM_{10} for SE and SW winds compared to the relatively flat elevated part of the NO_2 curve. Despite these differences, using the average deviation values in Figure 23 for wind directions from 130-230° and expressing the CO values in units of µg/m^3, the average CO:NO_2:PM_{10} ratio is found to be 50:3.4:0.5 for these roadway vehicle emissions.

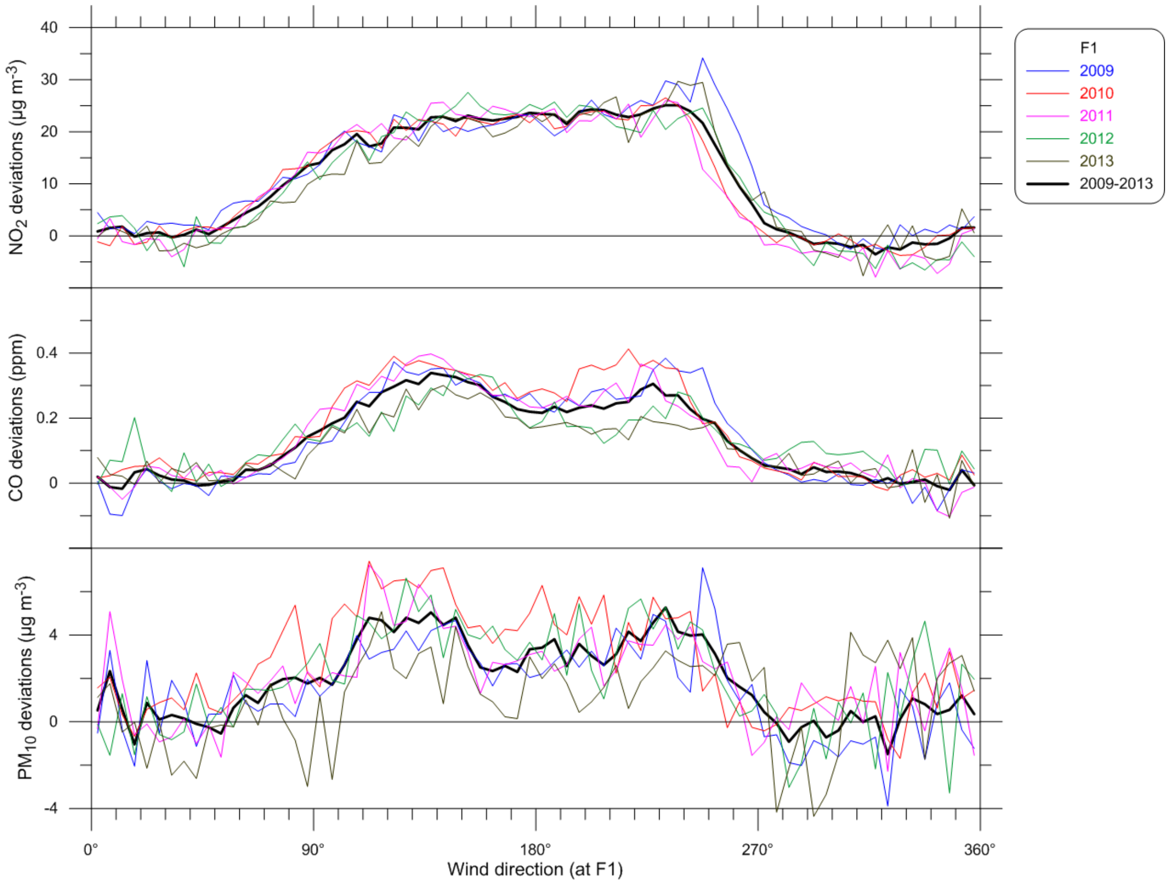


Figure 23 Average NO_2, CO and PM_{10} deviations at F1 from values at U1

Given that the source of the M5 stack emissions is the same vehicles as those travelling past the F1 site, it is useful to compare the above ratio with the ratio of 50:2:1 for M5 stack emissions (Table 10). The CO:NO_2 ratio for the motorway emission of 14.5:1 (range 12:1 to 18:1) is about half the estimated value of 25:1 for the stack emissions. The pollutant CO reacts very slowly so that the difference is due to conversion of some vehicle emissions of NO to NO_2 between the motorway and the monitoring site (e.g. NSW EPA, 2015). There is also relatively less PM_{10} near the motorway than at the stack (half or less), which could be due to the PM_{10} stack emissions including a higher proportion of tyre, brake and road dust than the open motorway.

4.4 Discussion

We consider in more detail the likelyM5 stack impact at CBMS identified in Figure 18. Specifically, we consider the questions:

- Why is it a “signal” and not just “noise”?
- Why is it a stack “signal” and not due to some other source(s)?
- Why isn’t it detected at monitoring sites that are closer to the stack?

Why is it a "signal" and not just "noise"?

Figure 24 shows deviations for each of the 5 years as well as the 5-year average for winds in the north-easterly quadrant to focus on the peak at 33°. The arrows are at the direction when the M5 stack is directly upwind of CBMS. The figure includes the results for all three pollutants – NO_2, CO and PM_{10} – with an offset applied to the curves so that the average for 0-90° winds is the same for each year. The top panel for NO_2 shows the presence of a peak at 33-38° and with a similar magnitude in each of the 5 years of data. It stands out above the noise. (Other panels are discussed below.) This year-to-year consistency confirms that it is not just a random occurrence or caused by a single unusual event in the data.

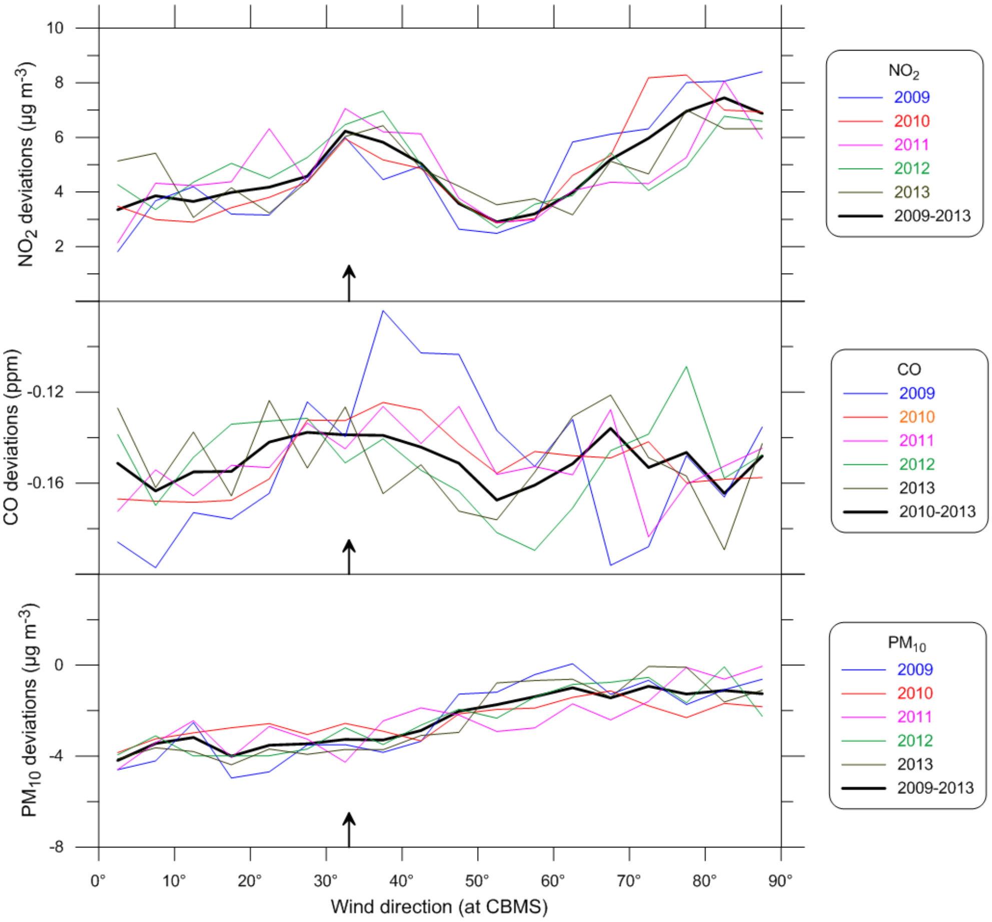


Figure 24 Average NO_2, CO and PM_{10} deviations at CBMS for winds in the NE quadrant. Note that for CO, the heavy black line is the 2010-2013 average because 2009 is an outlier.

An estimate of the noise in the 5-year average CBMS curve for NO_2 in Figure 16 is ±0.5 µg/m^3 (based on the standard deviation of differences between the curve and the 5-point moving average). The noise is similar in the T1, U1 and X1 curves. As can be seen in Figure 24, the noise is greater in the curves for each individual year and for NO_2 is estimated to be ±0.9 µg/m^3. Both values are smaller than the estimate of 2 µg/m^3 in Table 11. This is because of averaging in 5° wind sectors with a further reduction by averaging over 5 years. That is, the peak at CBMS of about 3 µg/m^3 in the NO_2 increment for winds blowing from the stack is well above the noise of about 0.5 µg/m^3; a signal-to-noise ratio of 6.

Why is it a stack "signal" and not due to some other source?

The strong alignment of the peak with the wind direction directly from the stack provides the initial strong evidence that it is a signal from the M5 stack.

The magnitude of the signal of 3 µg/m^3 is also consistent with the modelled maximum 1-hour average concentration of 2.5 µg/m^3 from previous modelling (Section 3.2), although the modelling did not account for additional NO_2 due to conversion of NO in the presence of ozone downwind from the stack.

The narrowness of the peak (compared for example to the broader SE and NW peaks) indicates that it is most likely a localised rather than diffuse source, probably a point source, which is consistent with the M5 stack being the source.

The wind direction of the peak provides a line along which the source is located but not its position. If it was located further upwind than the region of the M5 monitoring sites (to the NNE), then it would be apparent in the polar plots at the other main monitoring sites (T1, U1, X1) and at the same or larger magnitude but none of these sites show such a signal (Figure 19). A major source located between the M5 stack and CBMS could produce a similar signal but we are not aware of any such sources. The dominant NO_2 sources between the stack and CBMS are vehicle emissions but these are diffuse and not sufficiently intense to produce the observed narrow peak.

The lower two panels of Figure 24 do not show a CO or PM_{10} peak corresponding to that for NO_2. There is a small increase in CO deviations from 25-45° but it is broader than the NO_2 peak. Therefore, we ask how large would we expect the corresponding signal in CO and PM_{10} to be for the 3 µg/m^3 NO_2 peak if the source is the m5 stack? Table 10 list the ratio of pollutant emission rates from the M5 stack as $CO:NO_2:PM_{10}$ = 50:2:1 with 8 times as much NO as NO_2 emitted. We know that some or all the NO is converted to NO_2 in the plume as it travels from the stack to CBMS (NSW EPA 2015, 2016) but we don't know the extent of the conversion; this depends on ambient ozone concentrations. If all the NO is converted to NO_2, then the observed ratio would be 50:18:1. The data from the near motorway site F1 (Section 4.3) showed the ratio as 50:3.4:0.5. We can use these two sets of ratios to determine the range of CO and PM_{10} concentrations that would be associated with a 3 µg/m^3 NO_2 peak. They are as follows, with the lower value being for full $NO \rightarrow NO_2$ conversion:

- CO: 0.007-0.06 ppm (8-75 µg/m^3)
- PM_{10}: 0.17-0.44 µg/m^3.

Using the same technique as for the NO_2 data, the noise in the 5-year average data in Figure 24 was estimated to be 0.01 ppm for CO and 0.3 µg/m^3 for PM_{10}. Noting that a signal can generally only be reliably identified if it is at least 3 times larger than the noise, the absence of CO and PM_{10} signal in Figure 24 indicates that the $NO \rightarrow NO_2$ conversion is greater than at F1, the near-motorway site. In other words, the source of the NO_2 is not nearby vehicle emissions. The absence of a detectable signal in the CO and PM_{10} data is consistent with the NO_2 peak being a stack signal.

Why isn't it detected at monitoring sites that are closer to the stack?

A remaining question is why a stack impact is only detected at CBMS and not at the other, closer monitoring sites. A likely reason at T1 is that this site is located in the bottom of the valley close to and at a similar height to the base of the stack, well below the top of the stack and the plume height and thus unlikely to be impacted by stack emissions. It should also be noted that it would be difficult to see a stack signal in the T1 polar plot because, if present, it would blend in with the generally higher deviations in the NW quadrant.

Although the elevations of U1 and X1 are closer to stack top, they are both located much closer to the stack (140 m and 357 m) than CBMS at 927 m. It is important to note here that the effective height of the stack is higher than the stack itself because of the effect of plume rise. This is the additional height that pollutants emitted from the stack are lifted to by the momentum and buoyancy of the emissions when they exit the top of the stack. The amount of plume rise is typically more than 50 m and is greater in light winds. As the wind blows the plume away from the stack, the plume spreads vertically (as well as horizontally) due to the mixing action of turbulence in the atmosphere. The vertical spread of the plume increases as the distance from the stack increases.

Thus, in relation to the absence of a stack impact at U1 and X1, it is possible that the plume is still well above ground level at these closer sites, whereas it has more time to mix down to the ground by the time it has travelled 927 m to the more elevated CBMS.

Based on this discussion in this section, especially the strong alignment of the peak with the wind direction directly from the M5 stack, it is concluded that the 3 µg/m^3 peak at CBMS is a measurable impact from M5 stack emissions.

Although the magnitude of the CBMS peak is about 3 µg/m^3, it should be noted that it only contributes about 0.15 µg/m^3 to the overall annual average NO_2 concentration at the site. A context for these values is the increases in concentration up to 30 µg/m^3 at the near-motorway monitoring sites F1 and M1 contributing to an increase of about 10 µg/m^3 in the annual averages. For reference, the NEPM standard for 1-hour average NO_2 concentrations is 246 µg/m^3.

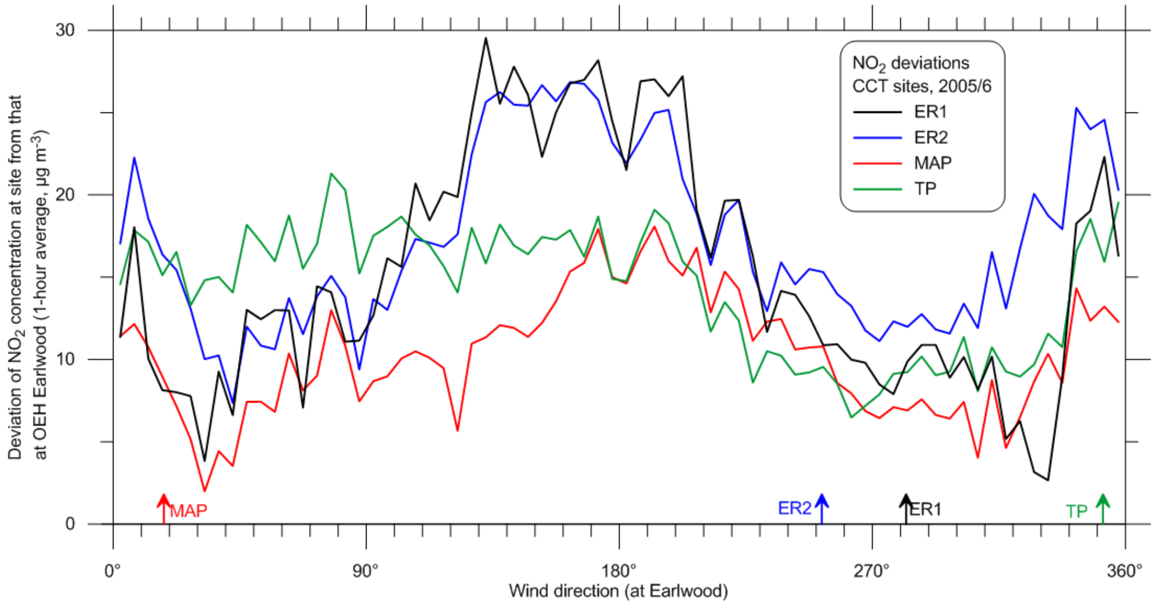
5 Is there a measurable impact at CCT sites?

Detailed scatter plots were analysed for each of the 4 CCT sites. These are included in the appendix (section 8) for NO_2 (Figure 41 to Figure 44), CO (Figure 45 to Figure 48), $PM_{2.5}$ (Figure 49 to Figure 52), and PM_{10} (Figure 53 to Figure 56).

There were no identifiable stack impacts at any of the 4 sites for any of the 4 pollutants (NO_2, CO, $PM_{2.5}$, PM_{10}). The summary plots of average deviations are shown in Figure 25 to Figure 27. They show generally noisier averages than for the M5 sites. This "noise" was quantified using the same technique as in Section 3.1 by analysing the differences between the concentrations at sites ER1 and ER2. The computed values are listed in Table 13 along with the values for the M5 sites, showing that the noise in the CCT site data is almost double that at the M5 sites for NO_2 and PM_{10} but slightly smaller for CO. Thus for any NO_2 signal at the CCT to be detected above the noise, it would need to be about twice as large as at the M5 sites.

Table 13. Comparison of "noise" in hourly concentrations at CCT and M5 sites

Pollutant	Standard deviation (σ)	
	CCT sites	M5 sites
NO_2	3.7 µg/m^3	2.0 µg/m^3
PM_{10}	2.5 µg/m^3	1.6 µg/m^3
$PM_{2.5}$	0.9 µg/m^3	-
CO	0.06 ppm	0.08 ppm



* Each arrow show the wind when the respective (same colour) monitoring site is directly downwind of the CCT stack

Figure 25 Average NO_2 deviations at the CCT sites vs wind direction for 2005-2006

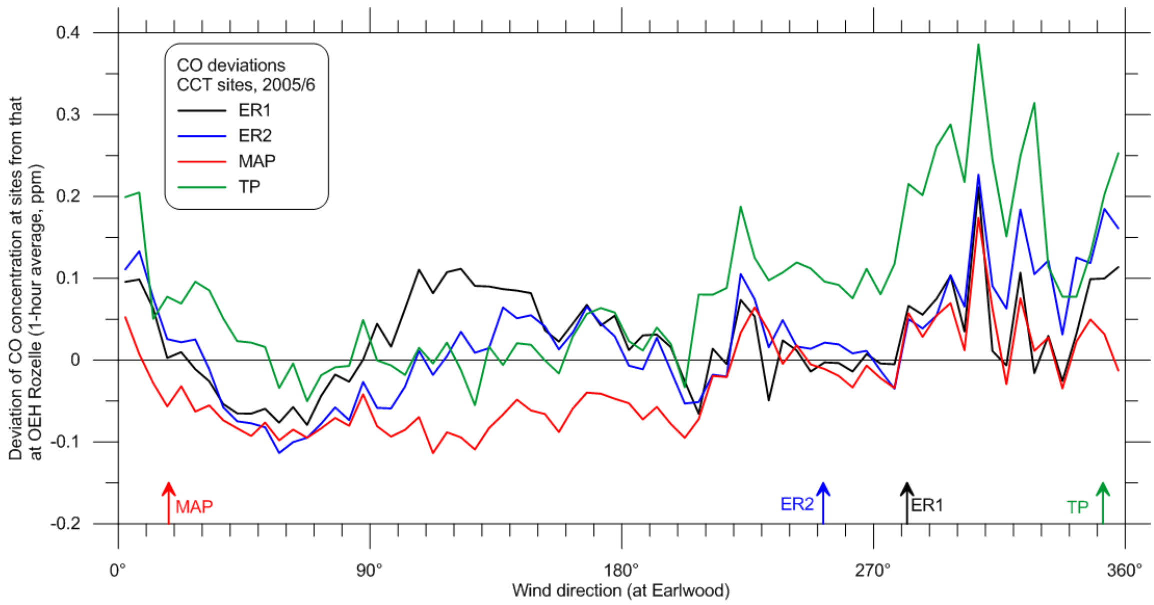


Figure 26 Average CO deviations at the CCT sites vs wind direction for 2005-2006

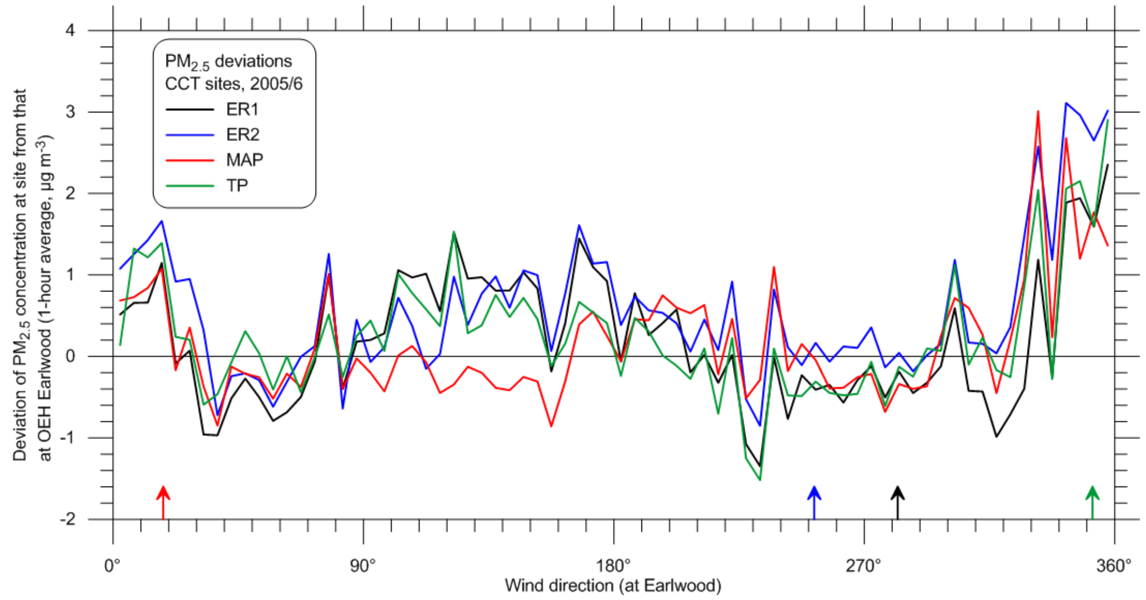


Figure 27 Average $PM_{2.5}$ deviations at the CCT sites vs wind direction for 2005-2006

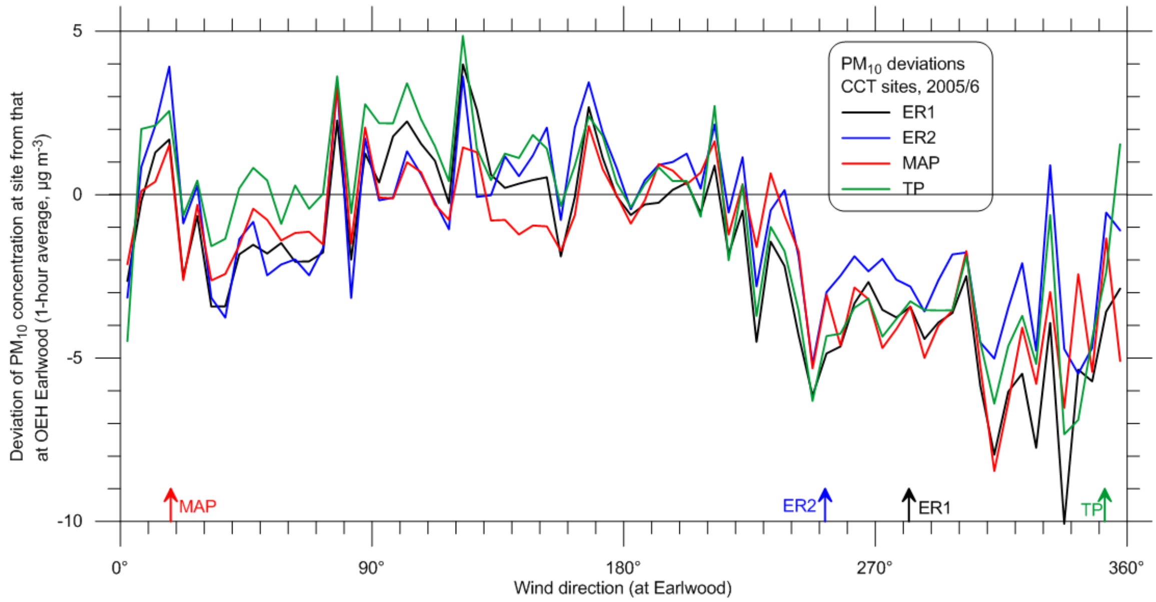


Figure 28 Average PM_{10} deviations at the CCT sites vs wind direction for 2005-2006

6 Conclusions

This study has analysed ambient monitoring data for 2009-2013 from sites near the M5 ventilation stack and for 2005-2006 from sites near the Cross City Tunnel (CCT) ventilation stack to address two questions:

(i) What is the potential for a measurable ambient air quality impact from the stack emissions?
(ii) Are any impacts from stack emissions discernible in the ambient monitoring data?

Potential for a measurable ambient air quality impact

The factors affecting the potential to detect a measurable air quality impact due to stack emissions are:

1. The “noise” (typical local variability) in the ambient monitoring data. By comparing the hour-by-hour differences in concentrations between two closely spaced monitoring sites, the noise in the data for the various pollutants were determined to be (see also Table 13):

    - NO_2 – 2.0 µg/m^3 at M5 sites, 3.7 µg/m^3 at CCT sites
    - PM_{10} – 1.6 µg/m^3 at M5 sites, 2.5 µg/m^3 at CCT sites
    - CO – 0.08 ppm at M5 sites, 0.06 ppm at CCT sites.

    The data averaging used in the analysis reduced the “noise” by about a factor of 5 in the final results.

2. The size of the impact, i.e. the incremental increase in ground-level concentration due to the stack emissions, is also referred to as the “signal”. This must be sufficiently larger than the “noise” in the data. This value is generally not known a priori but is proportional to the emission rate of the pollutant. Thus the signal for a pollutant emitted at a higher rate will be larger than for a pollutant with a lower emission rate. These together with estimates for the noise can be used to compute the relative signal-to-noise ratios for each pollutant to determine which has the highest potential to be detected.

3. The monitoring site must be downwind of the stack. The proportion of time when this is the case varies considerably for the M5 sites. Including wind directions within ±10° of directly downwind from the stack, the proportion of hours when the sites are downwind is: T1 21%, CBMS 5.3%, U1 2.7%, and X1 1.3%.

4. If multiple pollutants can be detected, the ratio of the measured non-reactive pollutants (after accounting for background pollutant levels) should be the same as their concentrations in the vent stack to confirm the stack as a likely source. Because this ratio is the same for emissions from vehicles using roads or the tunnel, this is not a unique identifier (i.e. it is a necessary but not sufficient condition that stack emissions are the source).

Is there a measurable impact of stack emissions?

The analysis used in this study is to calculate for each hour the deviation of the 1-hour average concentration at the monitoring site from that at OEH Earlwood. The effect of this is to remove region-wide variations in the pollutant concentrations to show the influence of more local sources and potentially an impact from the M5 stack. These deviations are averaged in 5° wind direction bins and plotted versus wind direction. An advantage of this technique over some other statistical methods is that it allows for the graphical presentation of results including as polar plots, which can be easily understood by informed members of the community.

The analysis demonstrated the presence of a measurable stack impact at CBMS but not at any other M5 sites (three of which are closer to the stack), nor at any of the CCT sites. At CBMS which is downwind from the M5 stack for a wind direction of 33°, the impact was detected in the NO_2 data as a 3 µg/m^3 peak, which was significantly larger than the standard deviation of the noise of 0.5 µg/m^3. This peak was present in each of the 5 years of analysed data with some minor year-to-year differences. For reference, the NEPM standard for 1-hour average NO_2 concentrations is 246 µg/m^3.

Although the magnitude of the NO_2 peak is about 3 µg/m^3, it only contributes about 0.15 µg/m^3 to the overall annual average NO_2 concentration at the site. A context for these values is the observed increases in concentration by an average of 25 µg/m^3 at the near-motorway monitoring sites contributing to an increase of about 10 µg/m^3 in the annual averages. For reference, the NEPM standard for annual average NO_2 concentrations is 61.5 µg/m^3.

7 References

Bureau of Meteorology (1997). Guidelines for the siting and exposure of meteorological instruments and observing facilities. Observation specification No. 2013.1. See section 3.5. http://www.bom.gov.au/climate/cdo/about/observation_specification_2013.pdf

Hibberd, MF (2006). Modelling of NOx concentrations near the M5 stack (Sep-Nov 2003). Prepared for NSW Health – Environmental Health Branch. 28 pp.

NSW EPA (2015). Assessment Methodology for Nitrogen Dioxide as an Air Pollutant.

NSW EPA (2016). Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales.

Rheingrover, SW and Gordon, GE (1988). Wind-trajectory method for determining compositions of particles from major air pollution sources. Aerosol Science & Technology 8, 29-61.

8 Appendix of additional scatter plots

8.1 CO deviation scatter plots at M5 sites

Figure 29 to Figure 34 show the scatter plots of CO deviations versus wind direction for each of the M5 monitoring sites. The combined plot of the average deviations is shown earlier in Figure 20.

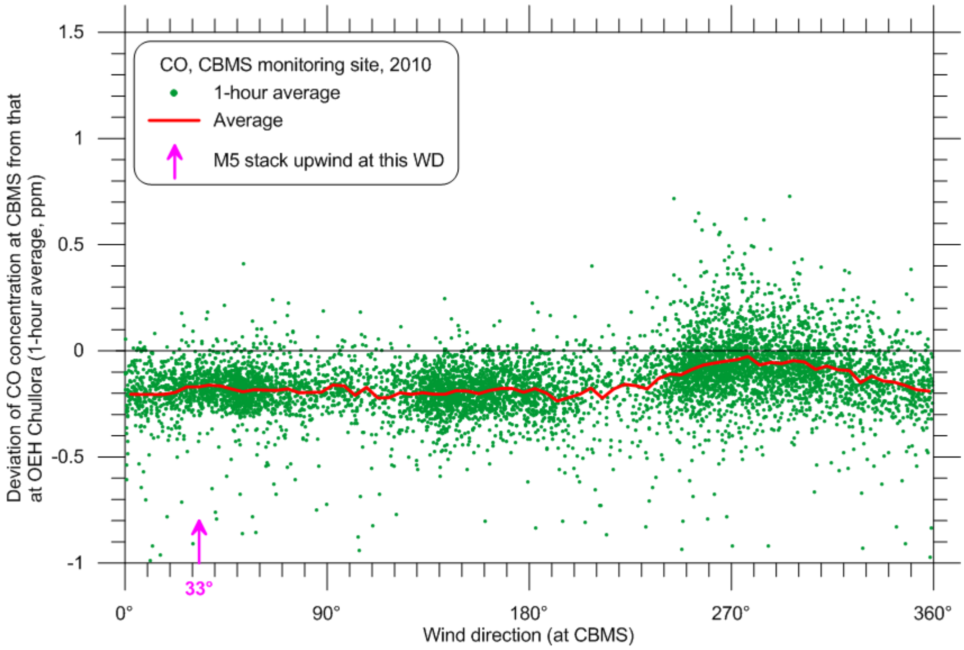


Figure 29 CO deviations at CBMS vs wind direction for 2010

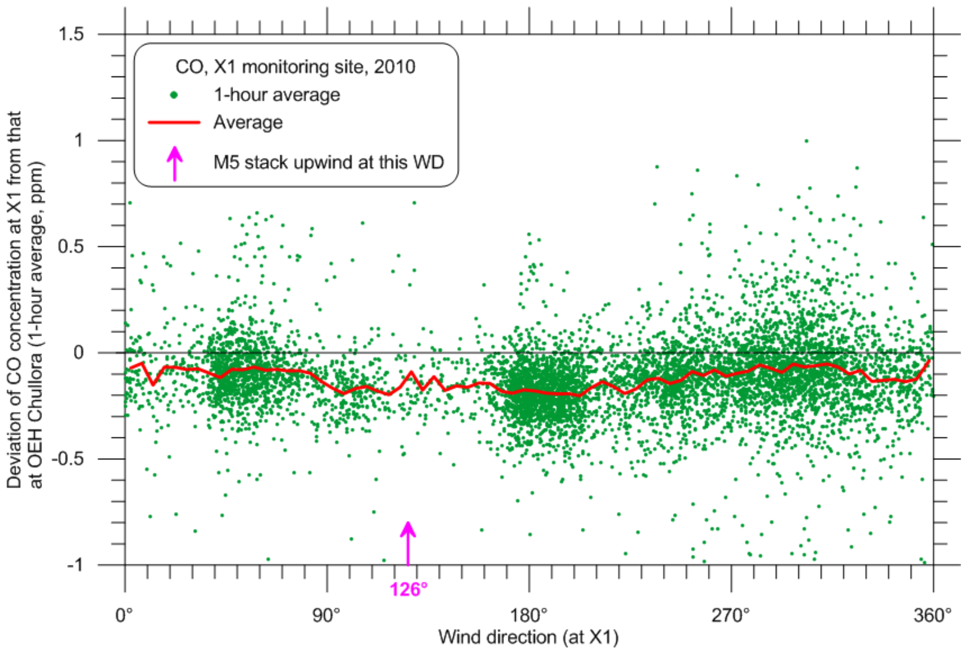


Figure 30 CO deviations at X1 vs wind direction for 2010

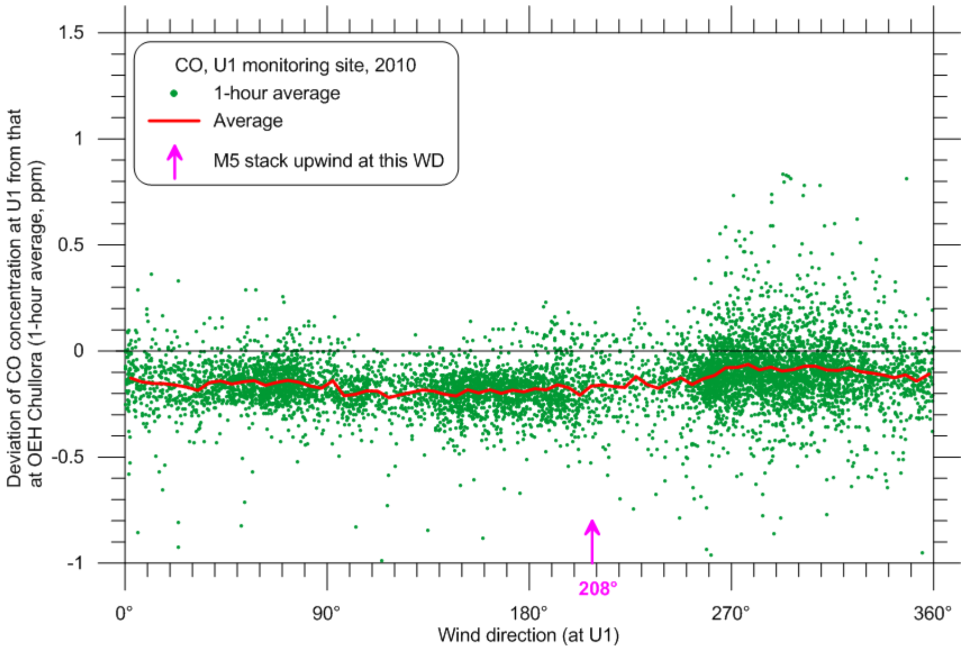


Figure 31 CO deviations at U1 vs wind direction for 2010

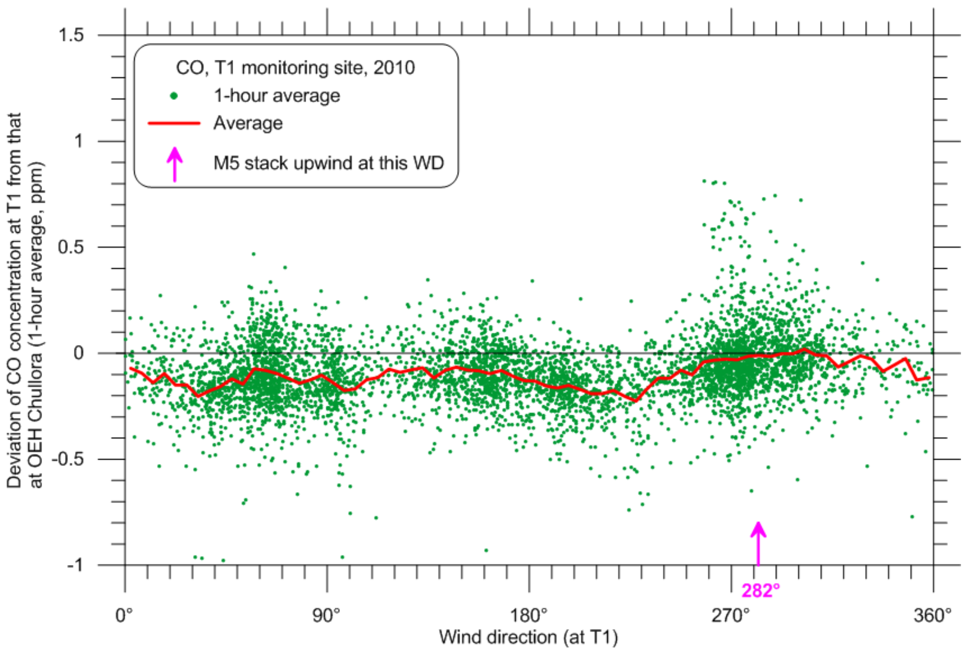


Figure 32 CO deviations at T1 vs wind direction for 2010

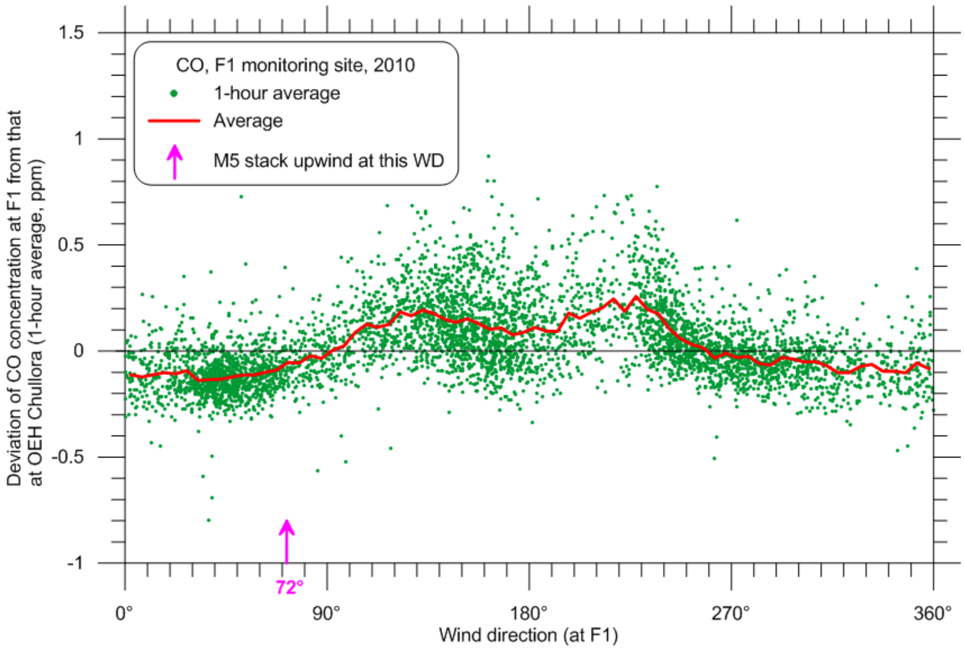


Figure 33 CO deviations at F1 vs wind direction for 2010

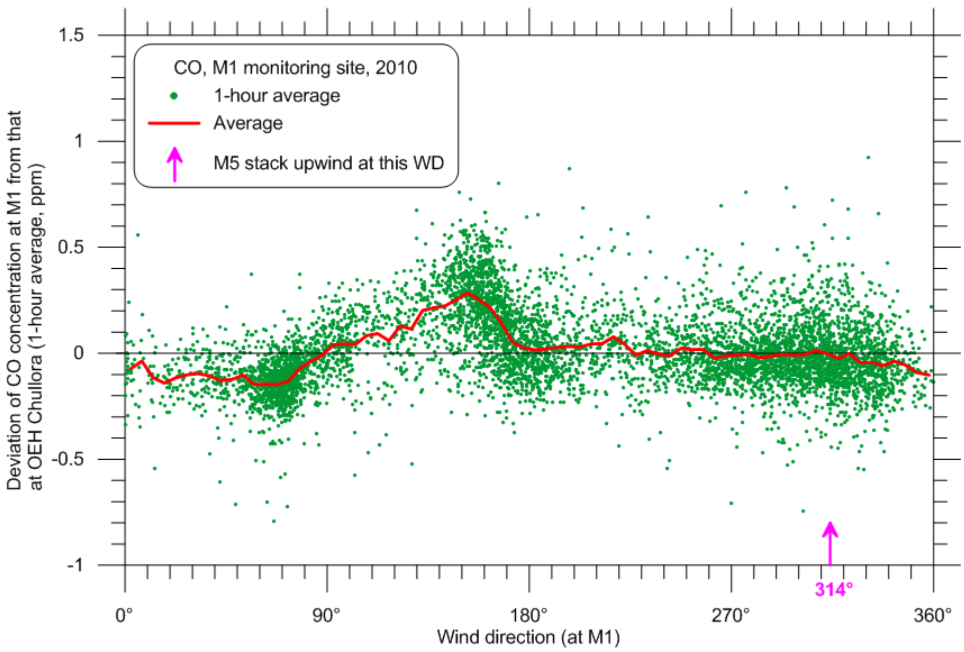


Figure 34 CO deviations at M1 vs wind direction for 2010

8.2 PM_{10} deviation scatter plots at M5 sites

Figure 35 to Figure 40 show the scatter plots of PM_{10} deviations versus wind direction for each of the M5 monitoring sites. The combined plot of the average deviations is shown earlier in Figure 21.

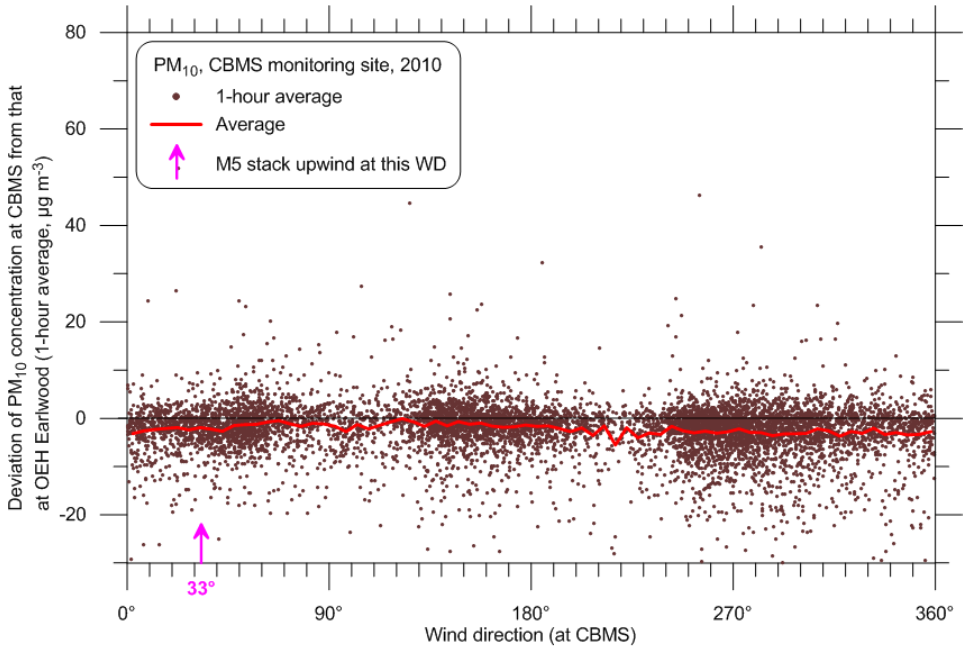


Figure 35 PM_{10} deviations at CBMS vs wind direction for 2010

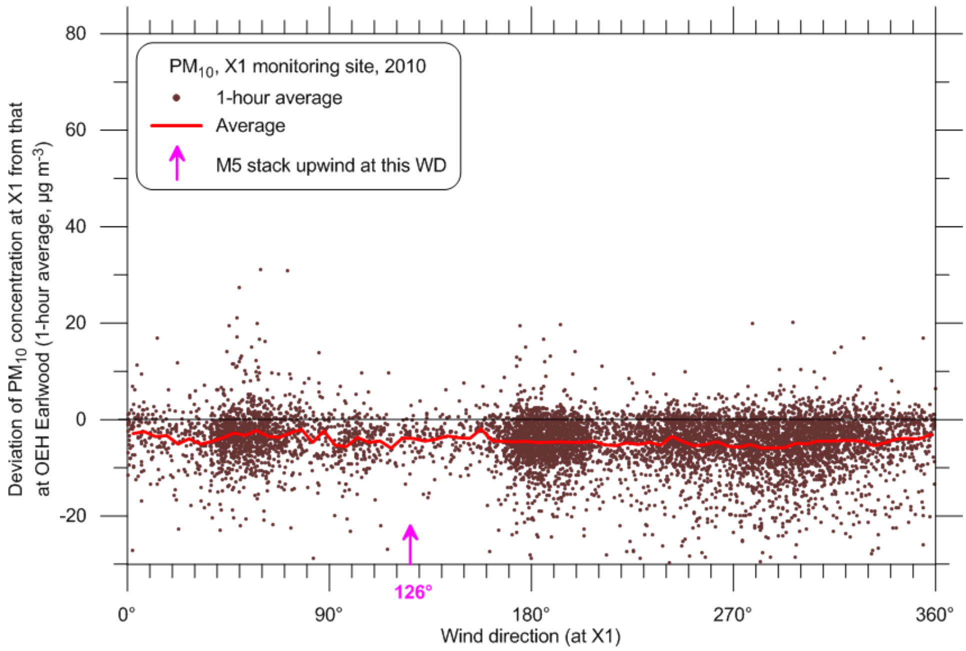


Figure 36 PM_{10} deviations at X1 vs wind direction for 2010

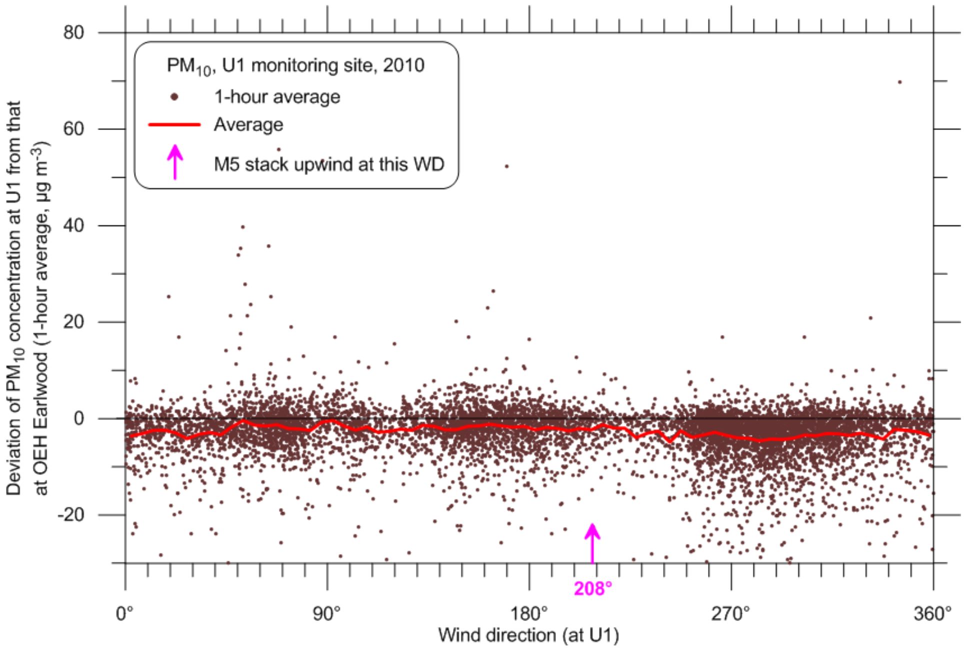


Figure 37 PM$_{10}$ deviations at U1 vs wind direction for 2010

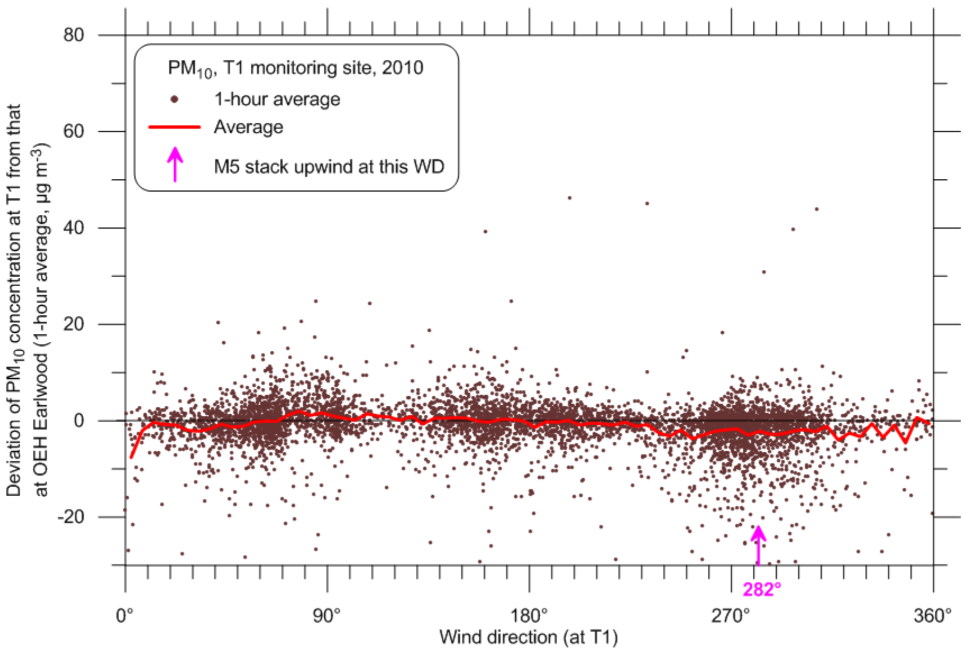


Figure 38 PM$_{10}$ deviations at T1 vs wind direction for 2010

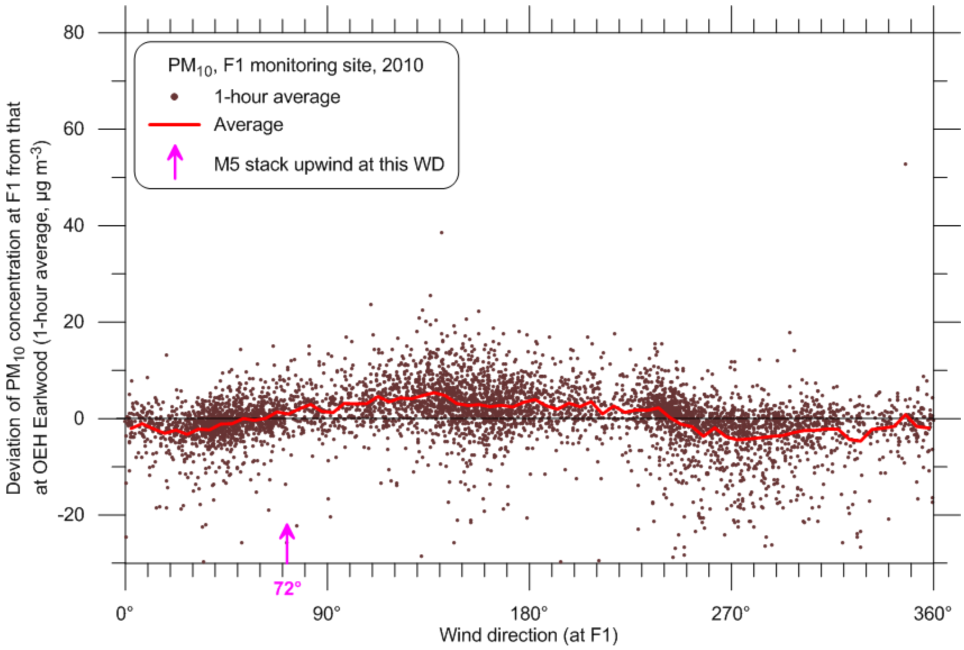


Figure 39 PM_{10} deviations at F1 vs wind direction for 2010

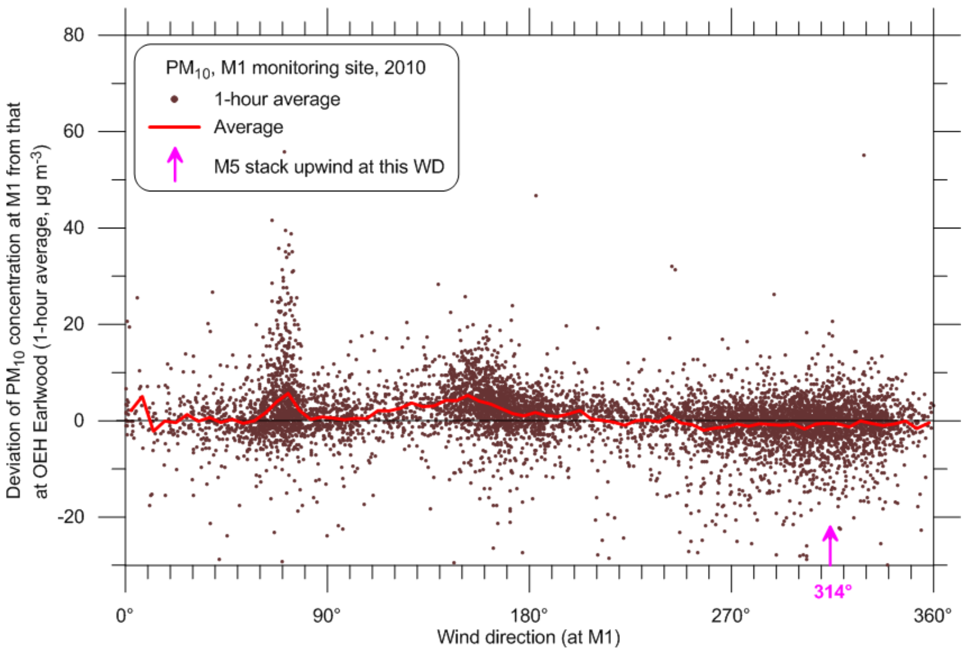


Figure 40 PM_{10} deviations at M1 vs wind direction for 2010

8.3 NO_2 scatter plots at CCT sites

Figure 41 to Figure 44 show the scatter plots of NO_2 deviations versus wind direction for each of the CCT monitoring sites. The combined plot of the average deviations is shown earlier in Figure 25.

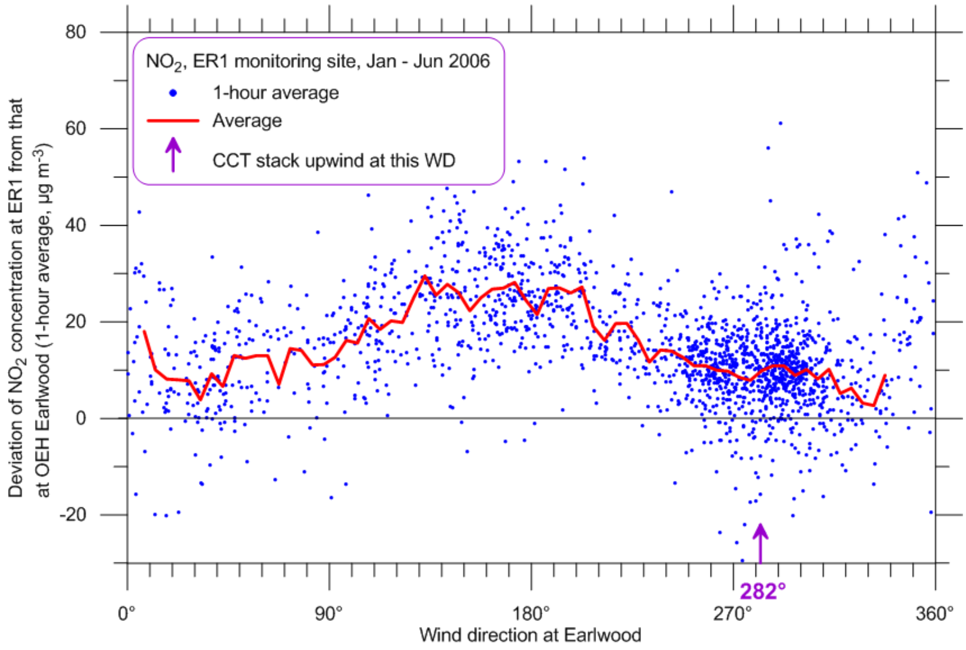


Figure 41 NO_2 deviations at ER1 vs wind direction for Jan-Jun 2006

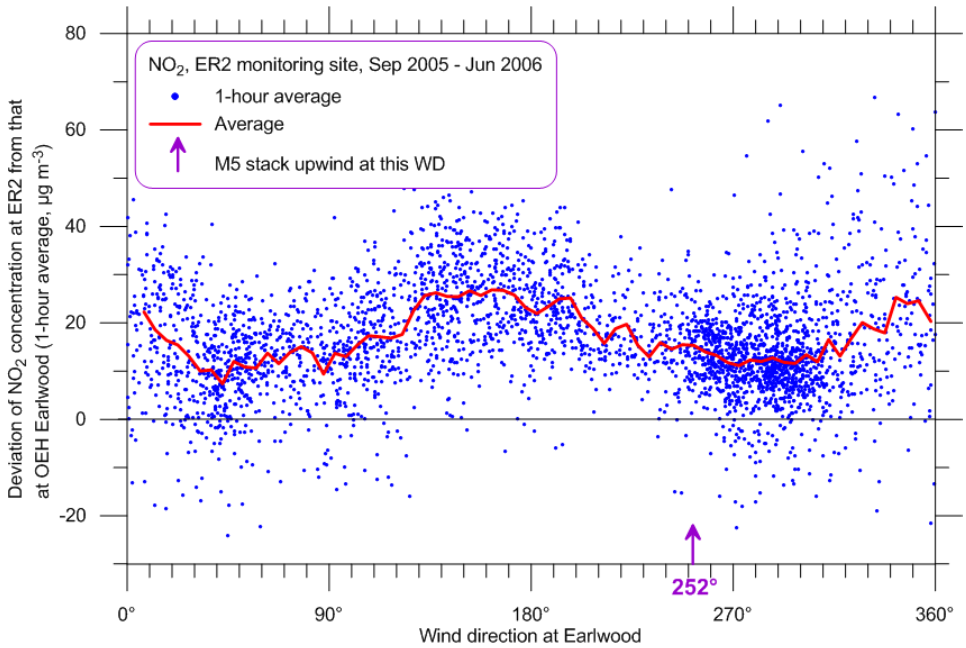


Figure 42 NO_2 deviations at ER2 vs wind direction for 2005-2006

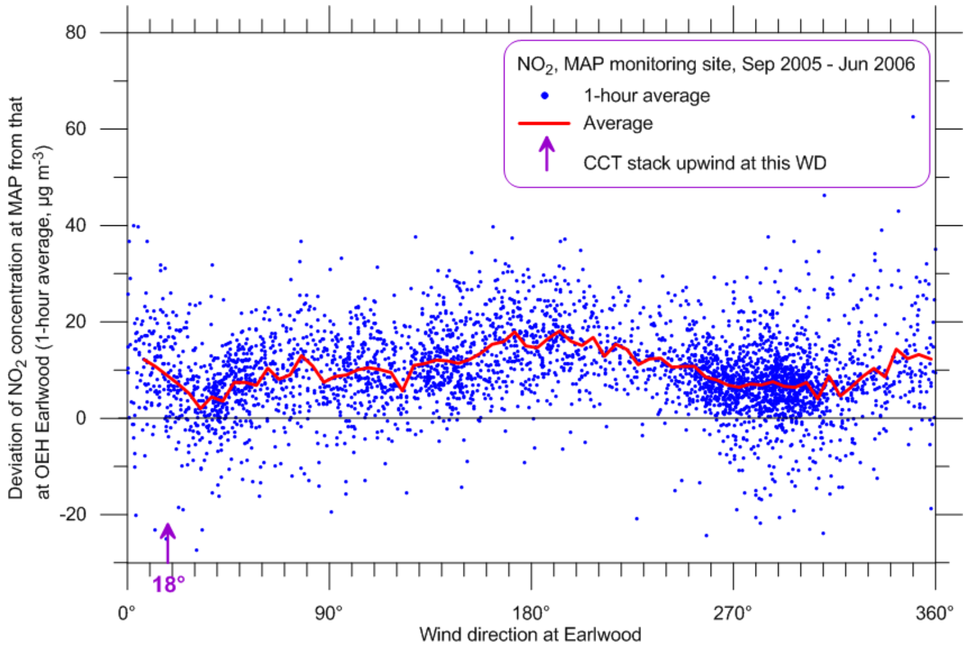


Figure 43 NO_2 deviations at MAP vs wind direction for 2005-2006

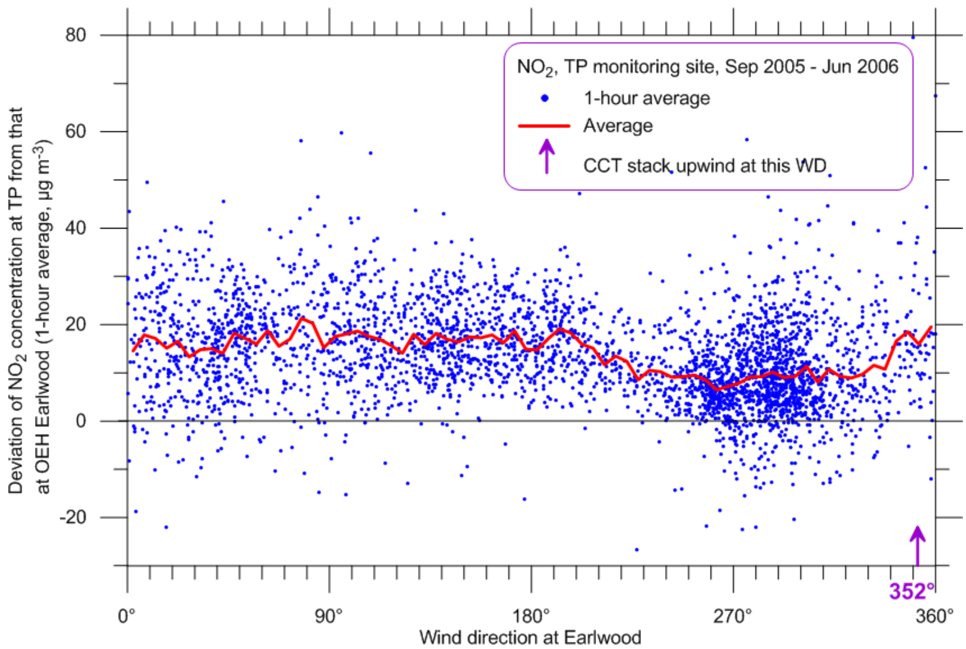


Figure 44 NO_2 deviations at TP vs wind direction for 2005-2006

8.4 CO scatter plots at CCT sites

Figure 45 to Figure 48 show the scatter plots of CO deviations versus wind direction for each of the CCT monitoring sites. The combined plot of the average deviations is shown earlier in Figure 26.

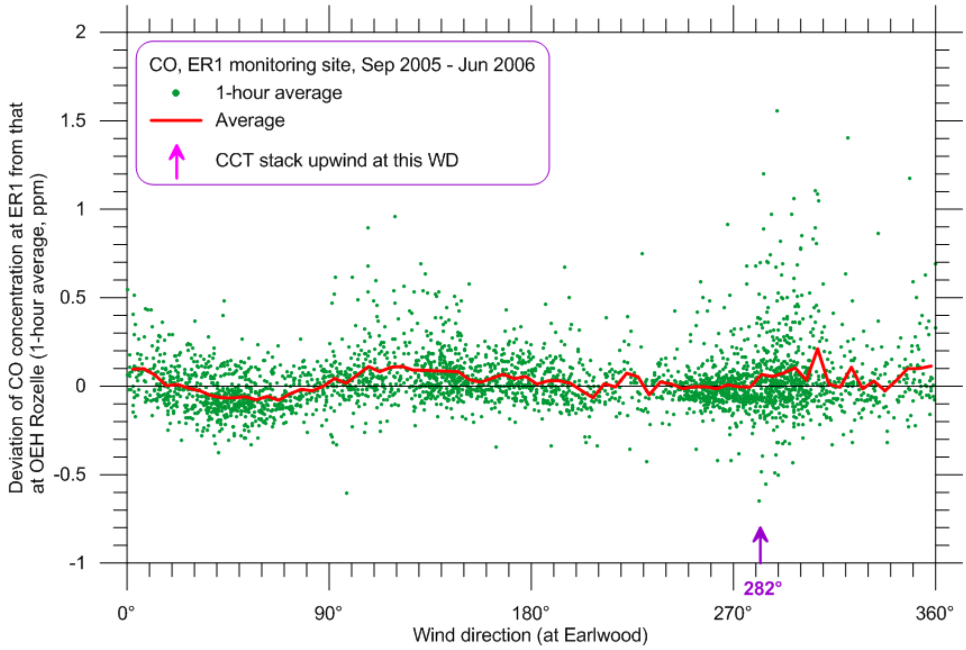


Figure 45 CO deviations at ER1 vs wind direction for 2005-2006

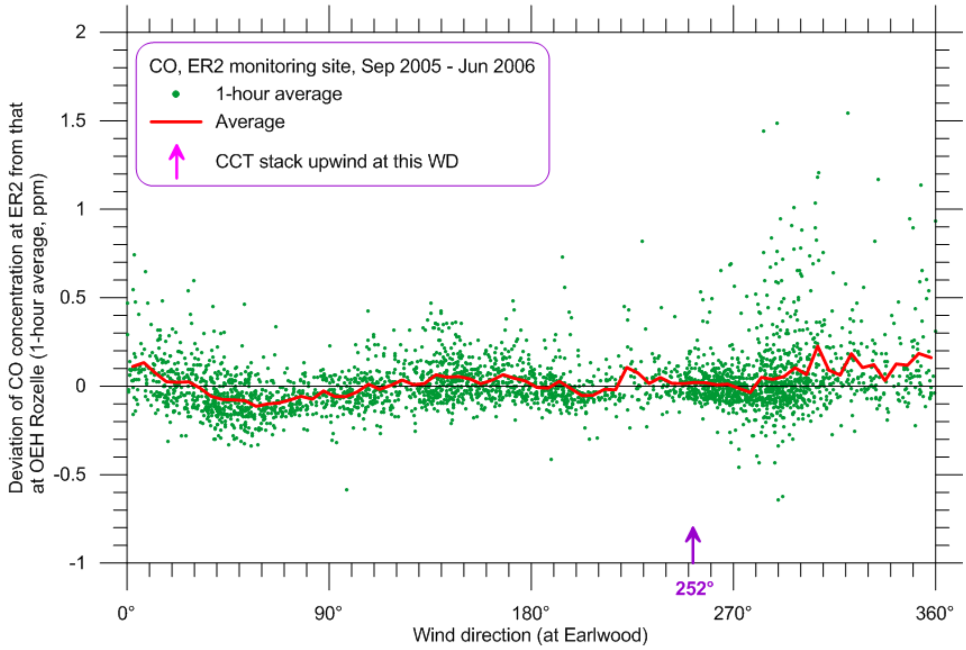


Figure 46 CO deviations at ER2 vs wind direction for 2005-2006

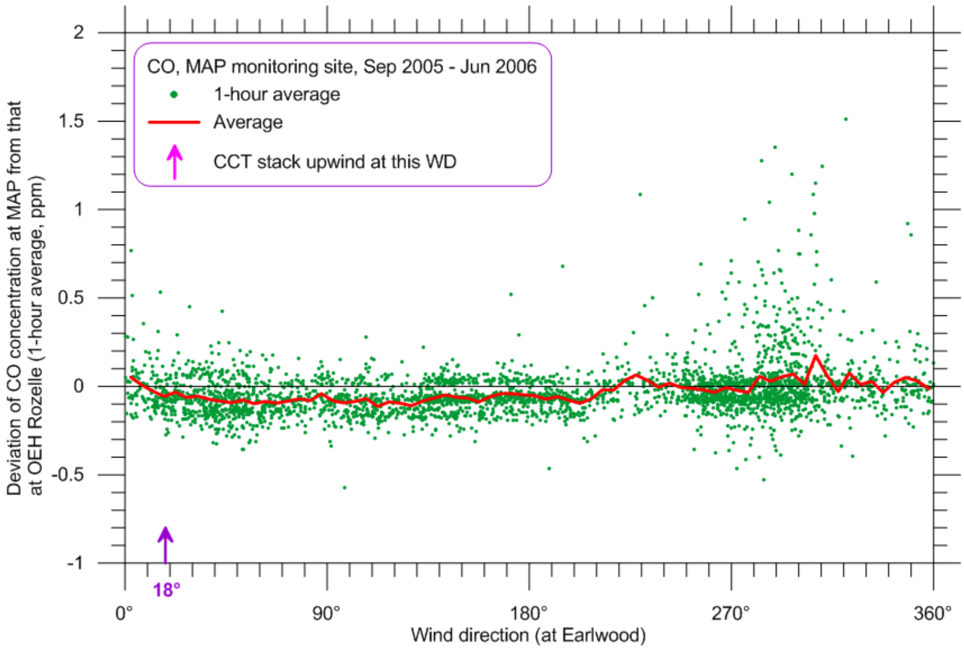


Figure 47 CO deviations at MAP vs wind direction for 2005-2006

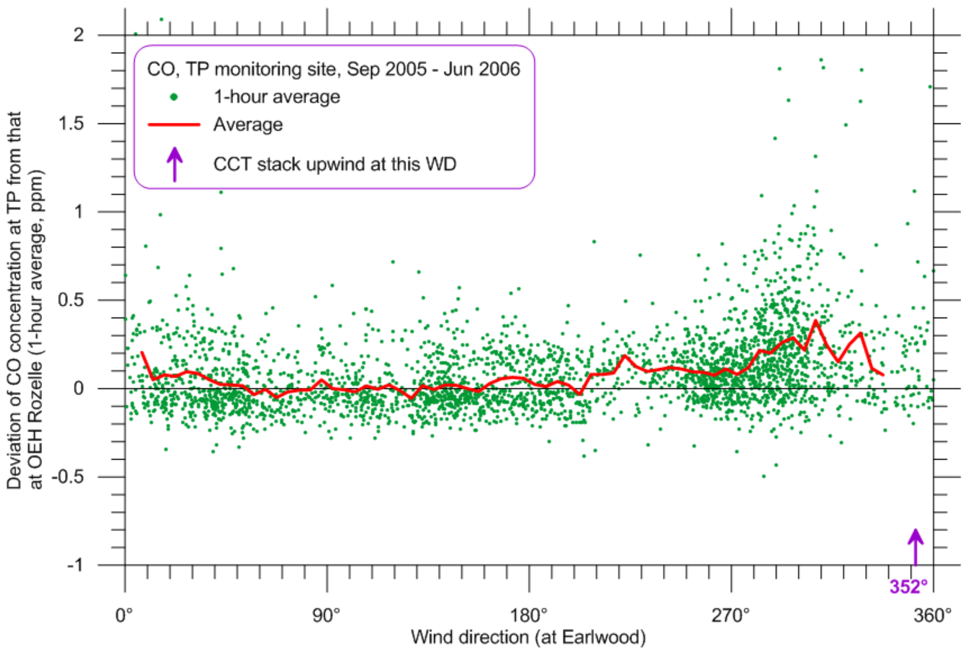


Figure 48 CO deviations at TP vs wind direction for 2005-2006

8.5 $PM_{2.5}$ scatter plots at CCT sites

Figure 49 to Figure 52 show the scatter plots of $PM_{2.5}$ deviations versus wind direction for each of the CCT monitoring sites. The combined plot of the average deviations is shown earlier in Figure 27.

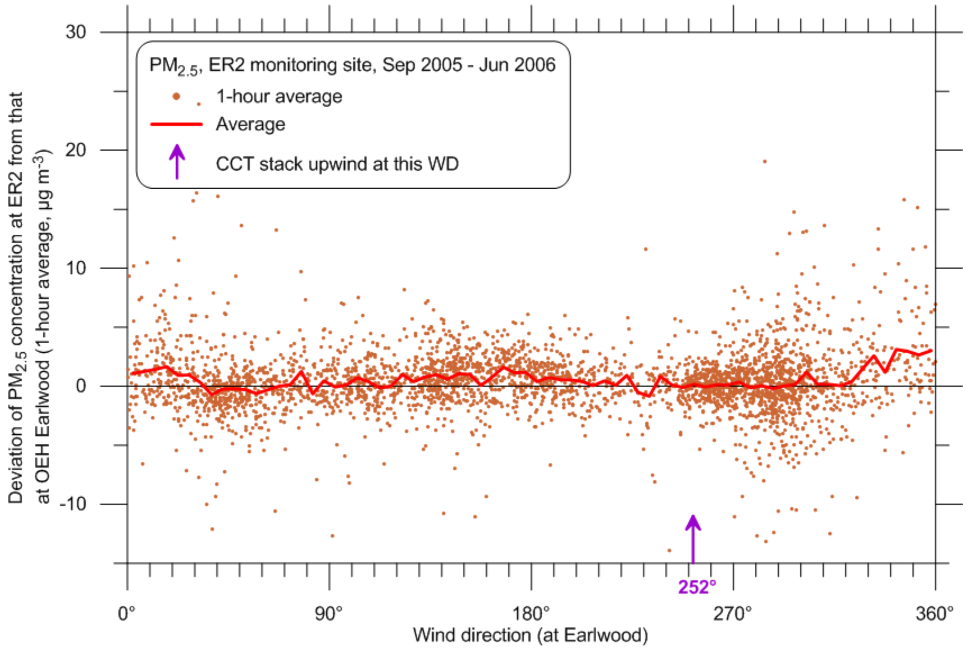


Figure 49 $PM_{2.5}$ deviations at ER1 vs wind direction for 2005-2006

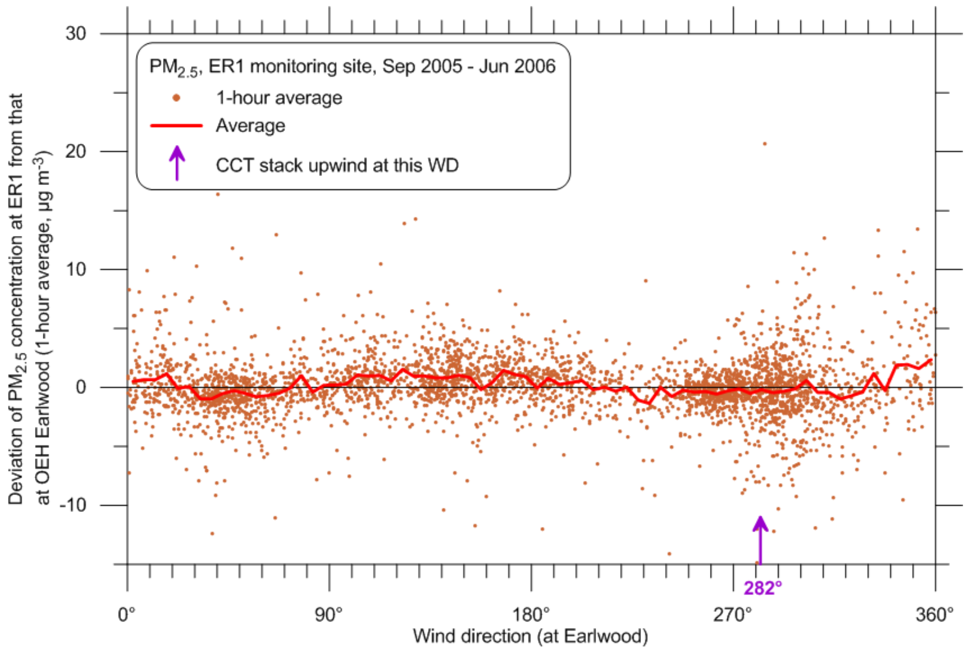


Figure 50 $PM_{2.5}$ deviations at ER2 vs wind direction for 2005-2006

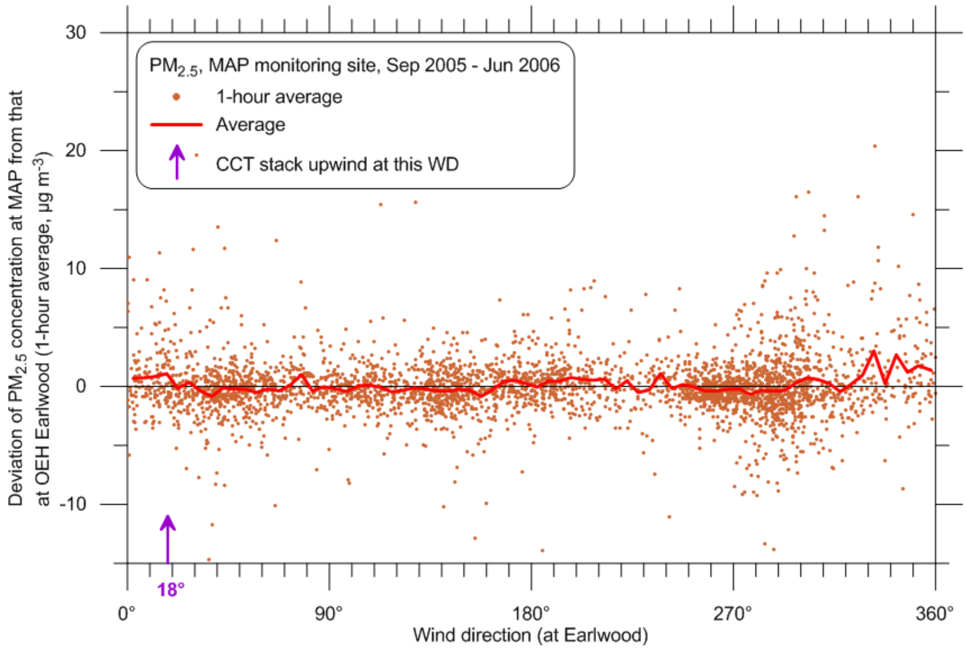


Figure 51 $PM_{2.5}$ deviations at MAP vs wind direction for 2005-2006

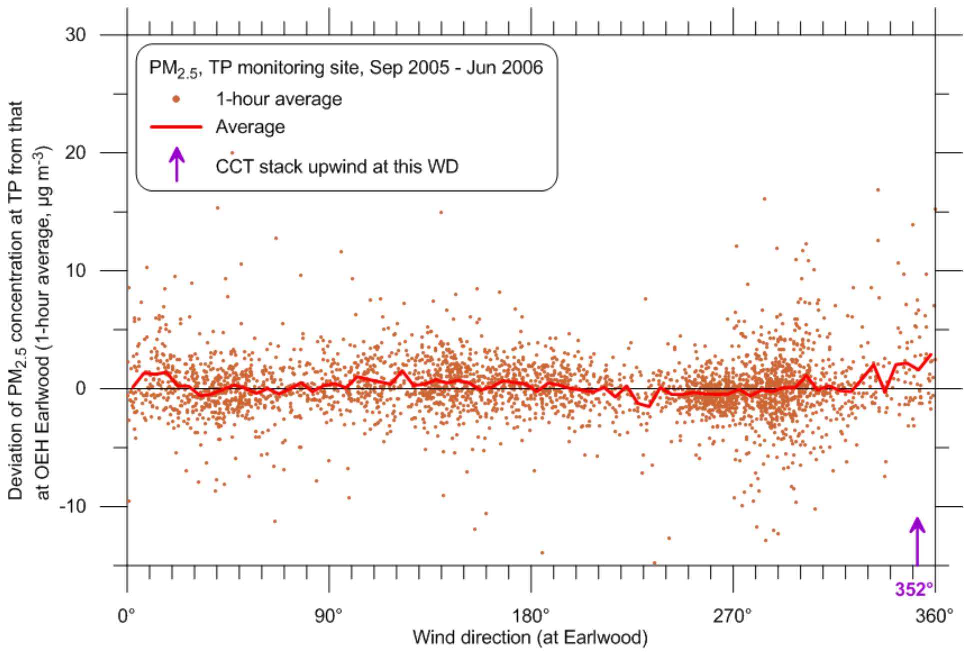


Figure 52 $PM_{2.5}$ deviations at TP vs wind direction for 2005-2006

8.6 PM_{10} scatter plots at CCT sites

Figure 53 to Figure 56 show the scatter plots of PM_{10} deviations versus wind direction for each of the CCT monitoring sites. The combined plot of the average deviations is shown earlier in Figure 28.

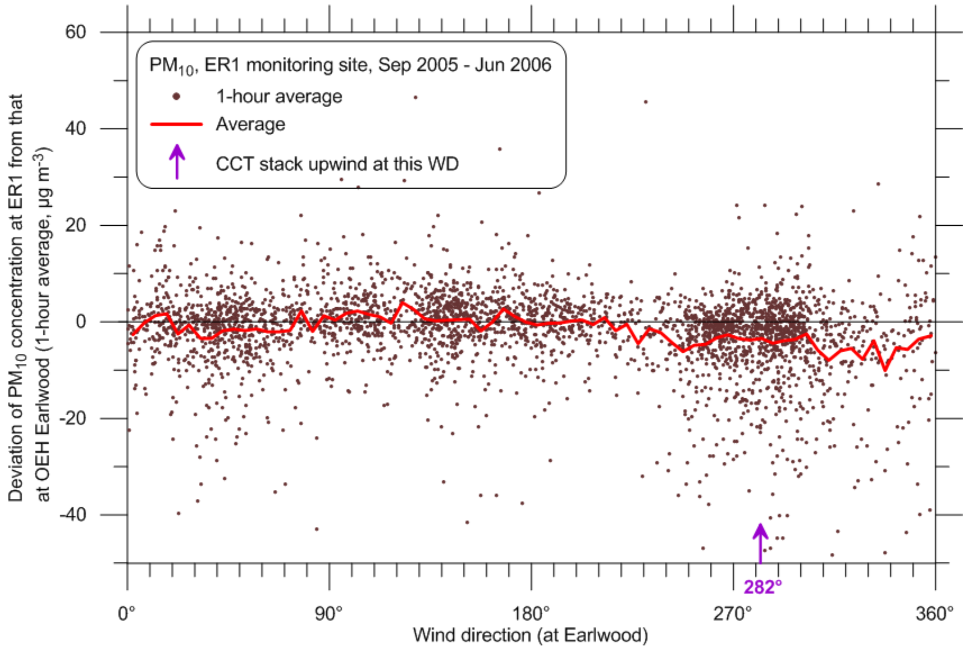


Figure 53 PM_{10} deviations at ER1 vs wind direction for 2005-2006

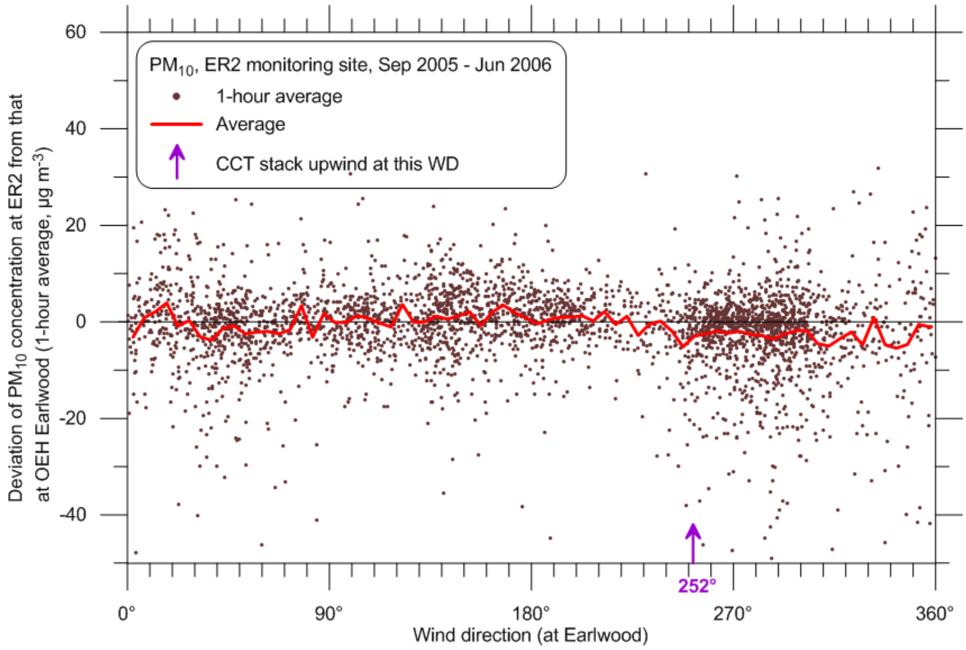


Figure 54 PM_{10} deviations at ER2 vs wind direction for 2005-2006

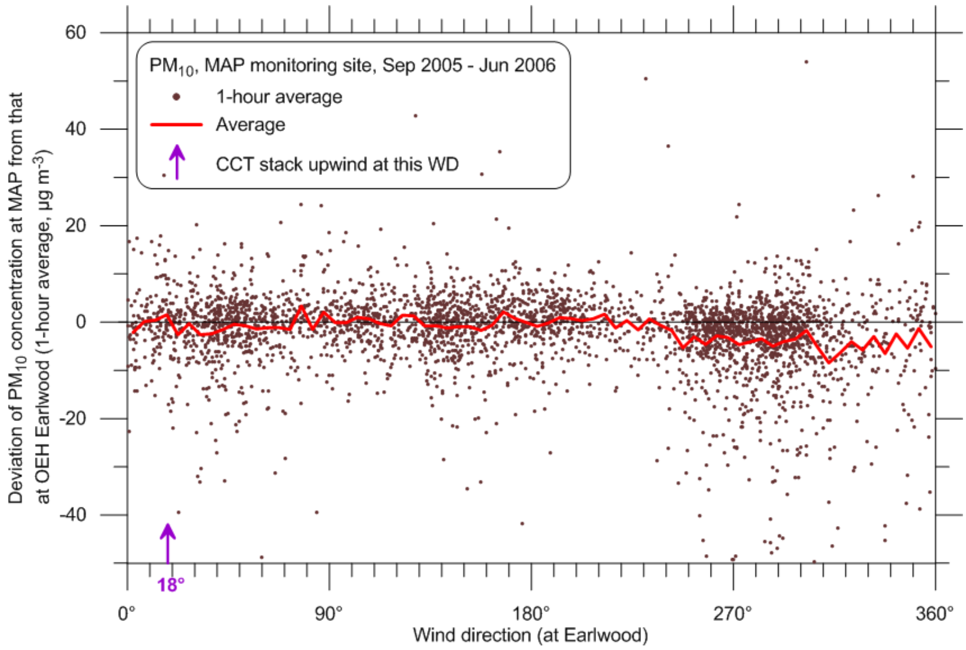


Figure 55 PM_{10} deviations at MAP vs wind direction for 2005-2006

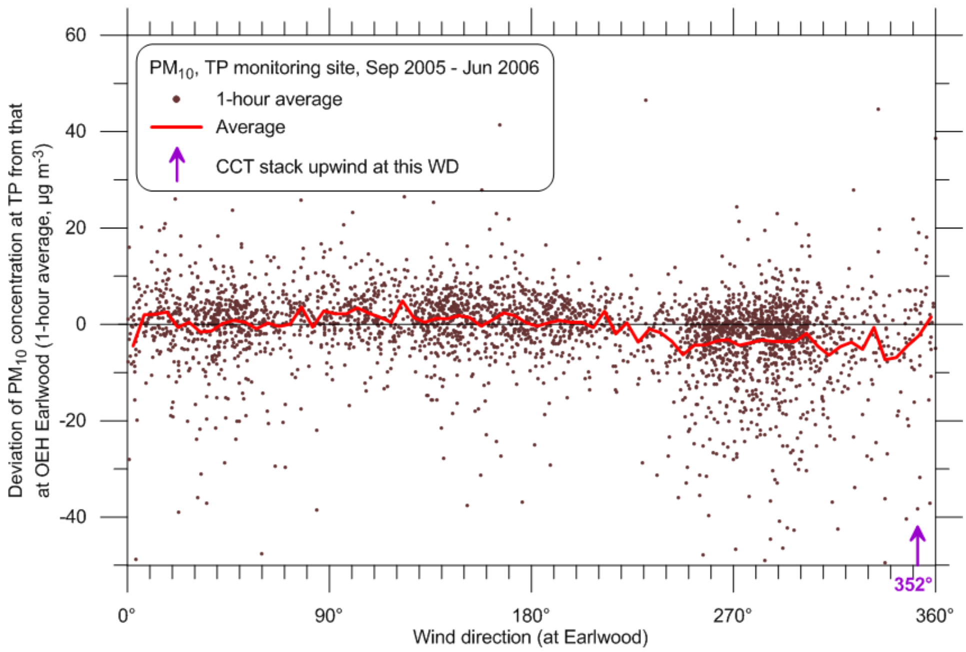


Figure 56 PM_{10} deviations at TP vs wind direction for 2005-2006