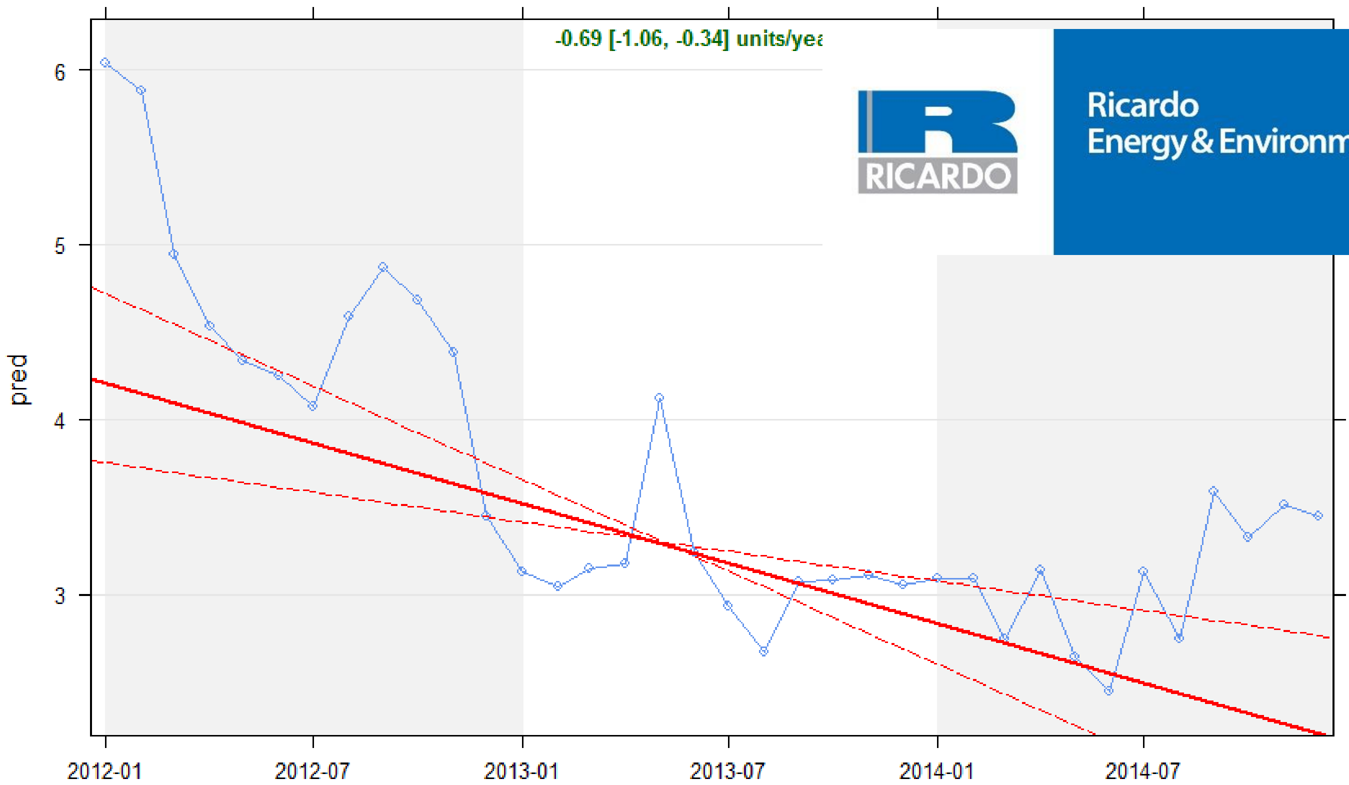

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Energy & Environment

De-weathering of Dundee Air Quality Data

Report for Dundee City Council

ED62349 | Issue 2 | Date 01/05/2018

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Dundee City Council

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Date:

01 May 2018

Ricardo Energy & Environment reference:

Ref: ED62349- Issue 2

Executive summary

Trends in Pollutant Concentrations

- Deweathered NO_2 concentrations remain unchanged during 2012 to 2016 at Mains Loan whilst a statistically significant decreasing trend in PM_{10} concentrations can be seen.
- Deweathered SO_2, PM_{10} (TEOM) and PM_{10} (Osiris) concentrations show a statistically significant decreasing trend during 2012 to 2016.
- In contrast to the trends at Broughty Ferry Road and Mains Loan, the deweathered trend in PM_{10} concentrations at Stannergate have no statistically significant trend during 2012 to 2016 with levels remaining relatively unchanged.

Pollutant Sources – Gaseous Pollutants

- The highest SO_2 concentrations were measured when the wind is from the south west, where an oil refinery is located.
- Maximum NO_2 concentrations at Broughty Ferry Road and Mains Road were measured with low wind speeds. The diurnal plots also show to that that road traffic is a main source of NOx at these sites.

Pollutant Sources – PM_{10}

- Similar polar plot profiles were seen at all sites with increased PM_{10} concentrations seen when the wind was from 95° to 135°, and from 190° to 260°, where 360° is north, indicating that here is a common source contributing to PM_{10} concentrations the three sites.
- Wind speed also has an influence on PM_{10} concentrations at all sites, with increased concentrations measured at wind speeds close to 0 ms^{-1} and greater than 10 ms^{-1} (22 mph) indicating that the source of increased PM_{10} is not local to the sites.
- The annual variation in polar plots for Mains Loan, Broughty Ferry Road and Stannergate. show that the sources of PM_{10} have not changed significantly between 2012 and 2016.
- The difference in the trend of PM_{10} concentrations at Stannergate indicate that there are additional sources of PM_{10} with increased concentrations measured when relatively strong wind (10 – 15 ms^{-1}) is from the east south east at approximately 100° where Dundee Docks and the Firth of Tay are located.
- Elevated concentrations at Stannergate are also seen at lower wind speeds with a wind from approximately 85° where the A930 is located relative to the site.
- Sea salt may also be a significant contributing factor at all three monitoring sites (Y. Qin, K. Oduyemi, 2003); the influence of high wind speeds and the wind direction resulting in increased PM_{10} concentrations is an indicator that this may be the case.
- An earlier study (Y. Qin, K. Oduyemi, 2003) also suggested that the European continent is a major source for secondary pollution species measured in Dundee which is likely to be a contributing factor to the increased concentrations seen at all sites when the wind is from the east.
- The Dundee Ports/Harbour which deals with dry bulk goods and the Firth of Tay are located to the south of all three sites and are likely to be a source of PM_{10}.

Table of contents

1 Introduction

1.1 Purpose of the Study

Ricardo Energy & Environment have been contracted by Dundee City Council to investigate trends in particulate matter (PM_{10}), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) concentrations during 2012 to 2016 at the following three air quality monitoring sites in Dundee:

- Dundee Broughty Ferry Road (SO_2 and PM_{10})
- Dundee Mains Loan (NO_2 and PM_{10})
- Dundee Stannergate (PM_{10})

The study aims to provide Dundee City Council with an assessment of potential sources and changes in pollutant concentrations at these sites.

1.2 Air Quality Strategy Objectives

The air quality objectives applicable to Local Air Quality Management (LAQM) in Scotland are set out in the Air Quality (Scotland) Regulations 2000 (Scottish SI 2000 No 97), the Air Quality (Scotland) (Amendment) Regulations 2002 (Scottish SI 2002 No 297). Table 1.1 summarises the AQS objectives for nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and particulate matter (PM_{10}) and shows the objectives in units of micrograms per cubic metre ($\mu g\ m^{-3}$) with the number of exceedances in each year that are permitted (where applicable).

Table 1.1 Air Quality Objectives included in Regulations for the purpose of LAQM

Pollutant	Air Quality Objective	
	Concentration	Measured as
Nitrogen Dioxide	200 $\mu g\ m^{-3}$, not to be exceeded more than 18 times a year	1-hour mean
	40 $\mu g\ m^{-3}$	Annual mean
Sulphur dioxide	350 $\mu g\ m^{-3}$, not to be exceeded more than 24 times a year	1-hour mean
	125 $\mu g\ m^{-3}$, not to be exceeded more than 3 times a year	24-hour mean
	266 $\mu g\ m^{-3}$, not to be exceeded more than 35 times a year	15-minute mean
Particulate Matter (PM_{10}) (Gravimetric)	50 $\mu g\ m^{-3}$, not to be exceeded more than 7 times a year	24-hour mean
	18 $\mu g\ m^{-3}$	Annual mean

2 Methodology

2.1 Monitoring Sites Used

Table 2.1 and Figure 2.1 show the locations of the air quality monitoring sites used for this study. Broughty Ferry Road and Stannergate are both located to the north of the Dundee Docks at roadside locations. Mains Loan is an urban background site, which provides information regarding city-wide background concentrations.

PM_{10} is measured using a Tapered Element Oscillating Microbalance (TEOM) at Mains Loan and Broughty Ferry Road. These data have been corrected using the Volatile Correction Model (VCM - http://www.volatile-correction-model.info/Default.aspx) for reference equivalent mass concentrations. Osiris indicative PM_{10} analysers are also used at Broughty Ferry Road and Stannergate monitoring sites. Osiris data have been adjusted using colocations with TEOMs to derive correction factors on an annual basis. SO_2 was monitored at Broughty Ferry Road until 2014 and monitoring of NOx began in 2016.

Table 2.1 Dundee Automatic Air Quality Monitoring Sites Used for the Study

Site Name	Site Type	Lat /Lon	Pollutants Monitored
Dundee Broughty Ferry Road	Urban Industrial	56.467332, -2.943423	NOx, SO_2, PM_{10} (TEOM and Osiris)
Dundee Mains Loan	Urban Background	56.475434, -2.959861	NOx, PM_{10} (TEOM)
Dundee Strannergate	Roadside	56.468333, -2.921389	PM_{10} (Osiris)

2.2 Data Analysis

Two aspects of the data were investigated in the study:

- The trends in pollutant concentrations
- The location of potential sources resulting in increased pollutant concentrations

The statistical software 'R' (https://www.r-project.org/) and the openair package (http://www.openair-project.org/) was used to carry the analysis.

One of the problems when analysing air pollution data and in particular trends in air pollutant concentrations is knowing whether changes in concentration are due to a change in emissions or a change in meteorology. In reality, for most practical situations there is a combination of effects and it is not possible to easily understand the relative importance of meteorology versus changes in emissions.

These difficulties have important consequences for understanding air pollution. It can mean, for example, that there is low uncertainty that concentrations have reduced due to emissions. Perhaps more importantly, interventions that affect air pollution can be virtually impossible to detect and verify because of the 'noise' due to meteorology.

There are however statistical techniques that can help with these issues. At a very simple level, if a statistical model can be built to 'explain' concentrations of pollutants in terms of different meteorological variables, then it should also be possible to use these models to predict concentrations under a defined set of conditions e.g. the most common weather conditions. This approach makes it possible to account for or 'remove' the effect of meteorology from trends to reveal trends that are much more strongly influenced by changes in emissions.

Figure 2.1 Dundee Automatic Air Quality Monitoring Sites Used for the Study

There are also other benefits to these types of approaches. For example, they can be used to help determine what the most important factors are that control concentrations. For air quality close to a motorway and with traffic data available, the influence of the traffic itself can be examined. For air pollution, many of the variations of pollutant concentration are highly complex. This makes it difficult to construct simple linear regression-type approaches that are effective. Moreover, many of the relationships are highly non-linear (e.g. with wind speed) and interactions between variables are very important (e.g. concentrations do not vary with wind speed in the same way for all wind directions).

In recent years there have been advances in statistical techniques - particularity in the 'machine learning' area. In the air quality area several modelling approaches have been used to account for meteorology in air quality data. This technique has been used to investigate the trends in pollutant concentrations in Dundee by removing the effect of weather from the data which helps provides a clearer picture of pollutant trends by removing the influence of meteorology on pollutant concentrations.

Figure 2.2 shows an example model built and associated influences for Mains Loan NO_2 concentrations between 2012 and 2016. For this study the influences of the following factors have been taken into account:

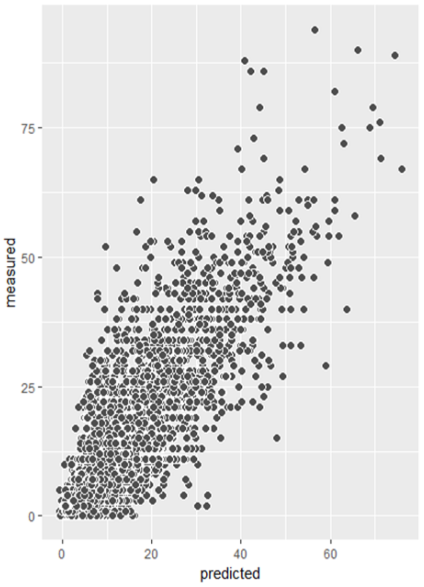
- The trend in NO_2 concentrations, trend
- Wind speed, ws
- Week of the year, week
- Ambient temperature, temp
- Weekday, weekday
- Hour of the day, hour
- Wind direction, wd
- Rainfall, rain

The scatter plot in Figure 2.2 shows how the model has performed well (r = 0.84) in predicting NO_2 concentrations against the measured values for a subsection of total number of hourly measurements (n = 7455 out of a total 43,802 hours). The summary statistics provided are:

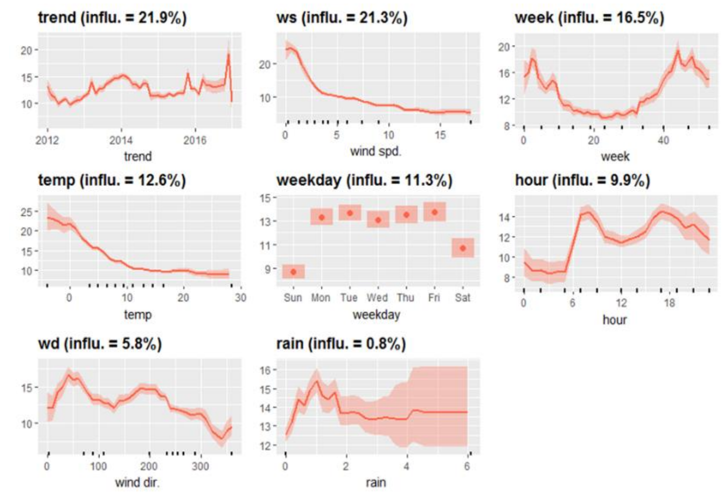
- Fraction of predictions within a factor of two, FAC2
- Mean bias, MB
- Mean gross error, MGE
- Normalised mean bias, NMB
- Normalised mean gross error, NMGE
- Root mean squared error, RMSE
- Correlation coefficient, r
- Mode coefficient, COE
- Index of agreement, IOA

In this case, the model indicates that the trend in pollutant concentrations has the greatest influence on the data (21.9%) followed closely by the wind speed (21.3%). The model also suggests that rainfall has least influence on NO_2 concentrations at Mains Loan.

Figure 2.2 Example Model and Associated Influences on Pollutant Concentrations



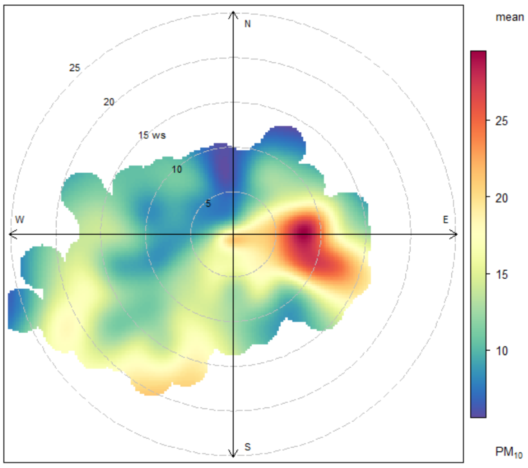
statistic	value
n	7455.00
FAC2	0.75
MB	0.01
MGE	4.08
NMB	0.00
NMGE	0.37
RMSE	6.11
r	0.84
COE	0.48
IOA	0.74



In terms of potential source of pollutants, bivariate polar plots are an effective way in which to gain information about sources of air pollution where wind direction and wind speed can reveal information about the character of sources. They show how concentrations vary by wind direction and wind speed, shown in polar coordinates. In addition, they show the concentration as a smoothed surface. Because pollutant concentrations vary in important ways when plotted against wind direction and speed they can provide insights into the character of the emission sources.

In these plots the radial axis is by default wind speed - changing from zero wind speed in the centre and increasing outwards. Figure 2.3 below shows an example polar plot for PM_{10} created using the openair package.

Figure 2.3 Example Polar Plot (µg m^{-3})



3 Results

The model results for the de-weathering of pollutant data are provided in Appendix 1.

3.1 De-weathered Trends

The following section details the derived 'de-weathered' trends for Mains Loan (NO_2 and PM_{10}), Broughty Ferry Road (SO_2 and PM_{10} (TEOM and Osiris)) and Stannergate (PM_{10} (Osiris)). Plots of the trends using unadjusted measurement data are provided in Appendix 2.

The trend analyses were done using the openair "TheilSen" tool. This uses the Theil-Sen statistical method to determine trends in pollutant concentrations over several years. The trend analysis is based on monthly mean pollutant concentrations.

In the plots, the trend line is shown by a solid red line, with 95% confidence intervals for the trend shown by dotted red lines. The trend is given at the top of the plot in green, with confidence intervals shown in square brackets. The trend is given as units (i.e. µg m^{-3}) per year, over the period shown. This may be followed by a number of stars, with * indicating that the trend is statistically significant at the 0.05 level, ** indicating significance at the 0.01 level and *** indicating significance at the 0.001 level. The symbol + indicates that the trend is significant at the 0.1 level.

3.1.1 Mains Loan

Figures 3.1 and 3.2 show the trends of NO_2 and PM_{10} concentrations, respectively. These results indicate that NO_2 concentrations remain unchanged during 2012 to 2016 whilst a statistically significant decreasing trend in PM_{10} concentrations can be seen. When compared to the trends seen in the unadjusted measurement data (Appendix 2), both the modelled and measured trends in NO_2 and PM_{10} agree.

Figure 3.1 Mains Loan De-Weathered Trend in NO_2 Concentrations

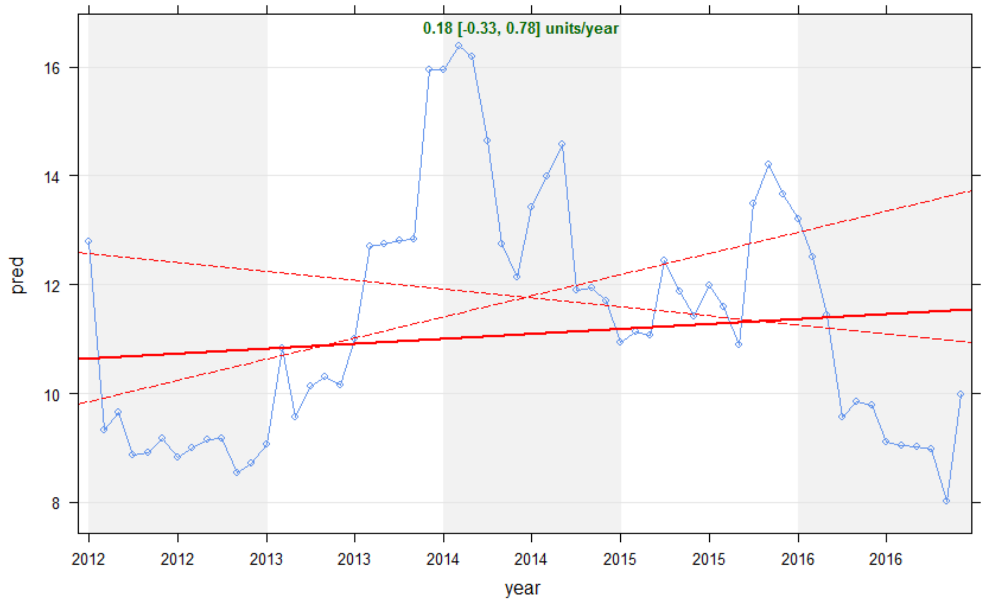
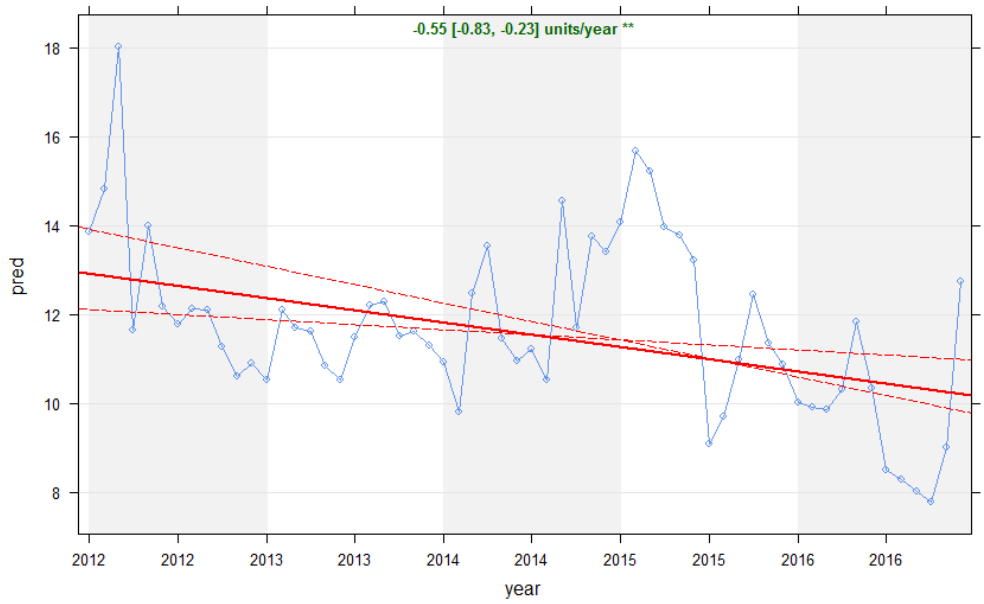


Figure 3.1 Mains Loan De-Weathered Trend in PM_{10} Concentrations



3.1.2 Broughty Ferry Road

Figures 3.3, 3.4 and 3.5 show the de-weathered trends in SO_2, PM_{10} (TEOM) and PM_{10} (Osiris), respectively. These results indicate that SO_2 and PM_{10} concentrations have a statistically significant decreasing trend during 2012 to 2016. When compared to the trends seen in the unadjusted measurement data (Appendix 2), both the modelled and measured trends in SO_2 and PM_{10} agree.

Figure 3.3 Broughty Ferry Road De-Weathered Trend in SO_2 Concentrations

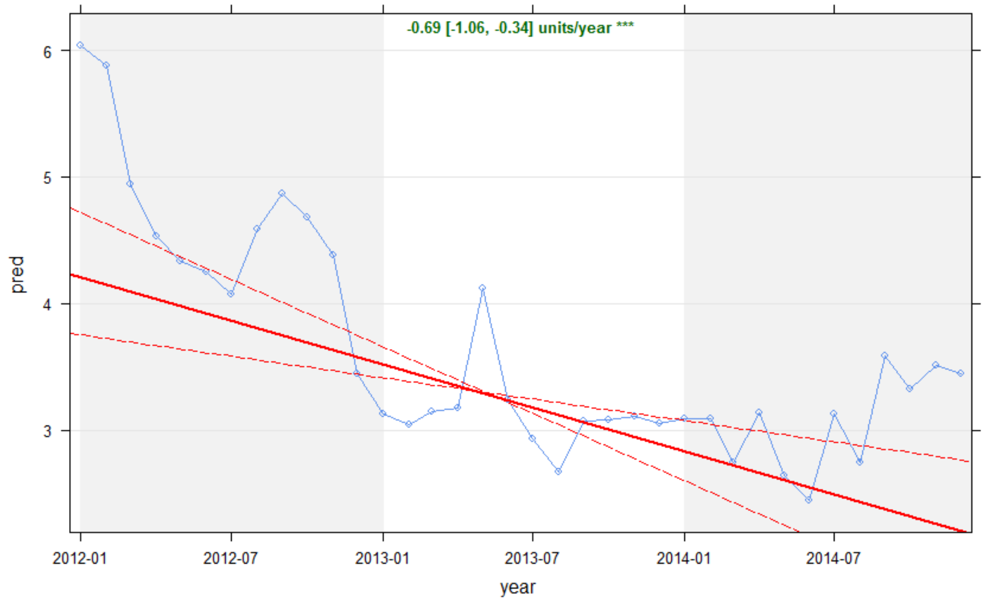


Figure 3.4 Broughty Ferry Road De-Weathered Trend in PM_{10} Concentrations

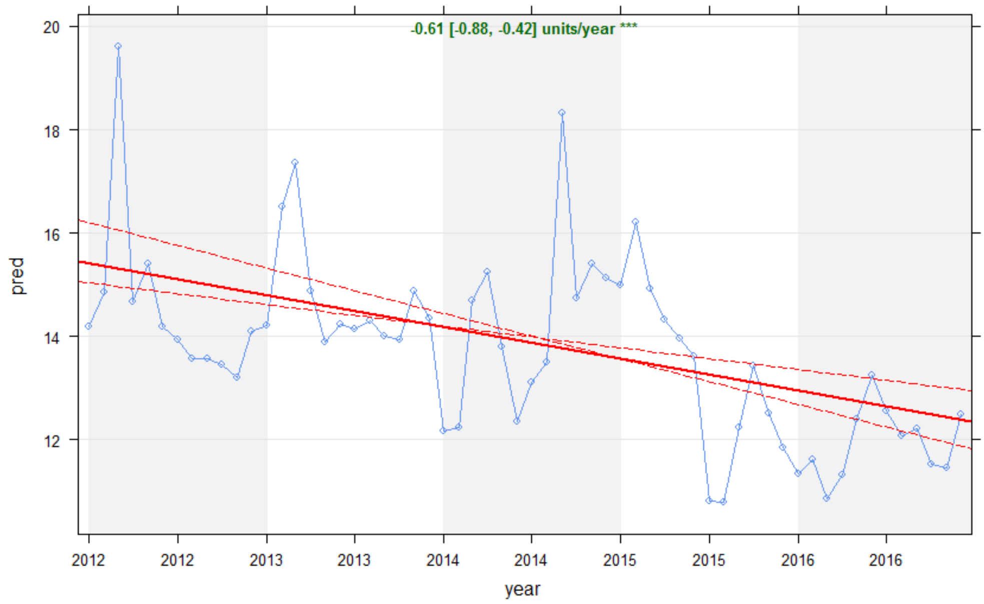
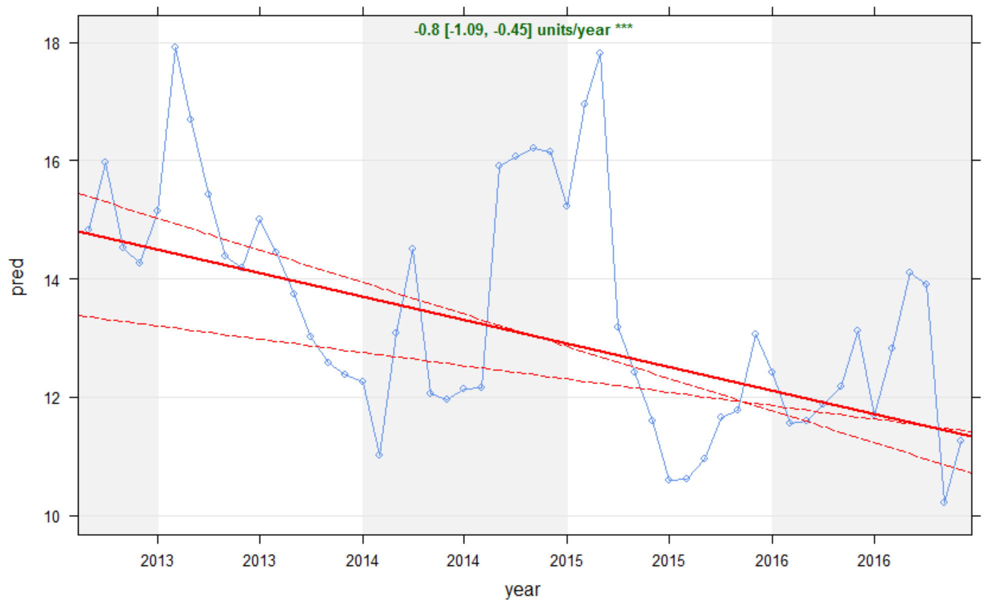


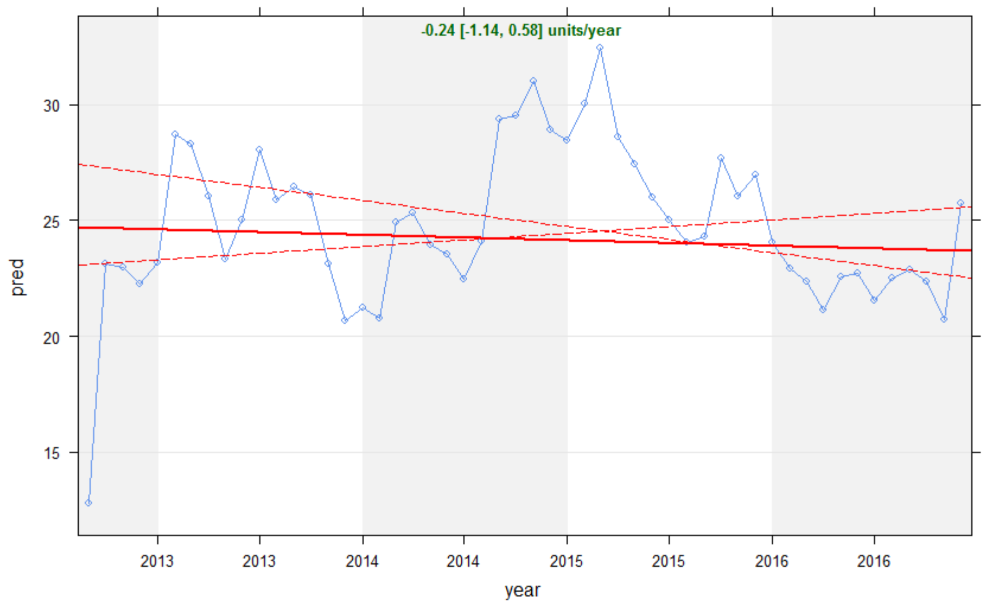
Figure 3.5 Broughty Ferry Road Osiris De-Weathered Trend in PM_{10} Concentrations



3.1.3 Stannergate

Figure 3.6 shows the de-weathered trend in PM_{10} (Osiris) concentrations at Stannergate. In contrast to the trends at Broughty Ferry Road and Mains Loan, these results indicate that PM_{10} concentrations have no statistically significant trend during 2012 to 2016 with levels remaining relatively unchanged. When compared to the trends seen in the unadjusted measurement data (Appendix 2), both the modelled and measured trends in PM_{10} agree.

Figure 3.6 Stannergate Osiris De-Weathered Trend in PM_{10} Concentrations



3.2 Source Analysis

3.2.1 Gaseous Pollutants

Table 3.1 summarises the influence of factors on NO_2 and SO_2 concentrations at Mains Loan and Broughty Ferry Road, respectively. For NO_2 at Mains Loan the main factors influencing concentrations are wind speed, ambient temperature and hour of the day. In this case, the analysis shows that NO_2 concentrations drop with wind speed and ambient temperature (Figure A1.1, Appendix 1), indicating that the source of increased NO_2 concentrations is close to the site. The hours of the day diurnal plot shows a typical traffic related pattern, with the highest concentrations measures at 8 am and 6 pm. This is also mirrored in the weekday plot where increased NO_2 concentrations are measure Monday to Friday.

The polar plot of NO_2 concentrations in Figure 3.7 and 3.10 confirms what was determined from the regression tree analysis. The plot shows that maximum NO_2 concentrations were measured when the wind speed was close to zero with a signal to the north of the site where a car park is located. The plot also shows that an increase in NO_2 was experienced when the wind was from the north west at higher wind speeds during 2012. This indicates that there was a source of NOx was located to the north east during 2012 and that the source was unlikely to be traffic related.

In terms of SO_2 at Broughty Ferry Road, the main influence is wind direction (Figure A1.3, Appendix 1). This shows that there is a specific source influencing concentrations. The polar plot in Figure 3.8 and 3.10 confirms this, with the highest SO_2 concentrations measured when the wind is from the south west where an oil refinery is located.

Similar to Mains Loan, maximum NO_2 concentrations were measured with low wind speeds (Figure 3.9). The diurnal plot is also similar to that at Mains Loan showing that road traffic is the main source of NO_2 at that site.

Table 3.1 Modelled Influence of Factors on NO_2 and PM_{10} Concentrations at Mains Loan

Factor	Modelled Influence NO_2 Concentrations, Mains Loan	Modelled Influence SO_2 Concentrations, Broughty Ferry Road
Ambient Temperature	18.3%	14.6%
Hour of the Day	15.2%	4.7%
Rainfall	1.0%	0.3%
Trend	13.9%	19.7%
Week of the Year	12.3%	5.4%
Weekday	9.5%	8.7%
Wind Direction	9.9%	37.5%
Wind Speed	20.0%	9.1%

Figure 3.7 Polar Plots of NO_2 Concentrations, Mains Loan ($\mu g\,m^{-3}$)

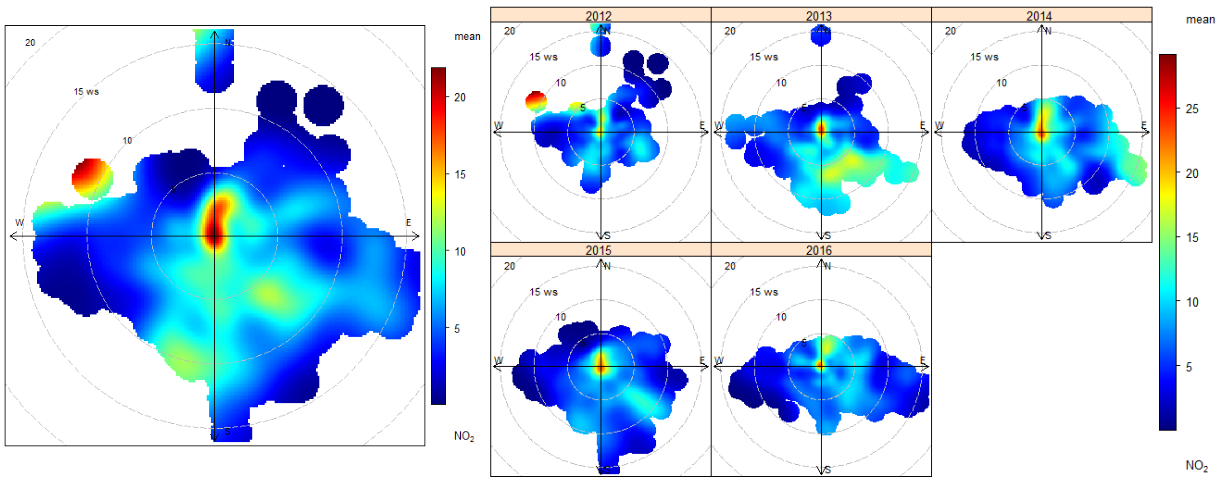


Figure 3.8 Polar Plots of SO_2 Concentrations, Broughty Ferry Road ($\mu g\ m^{-3}$)

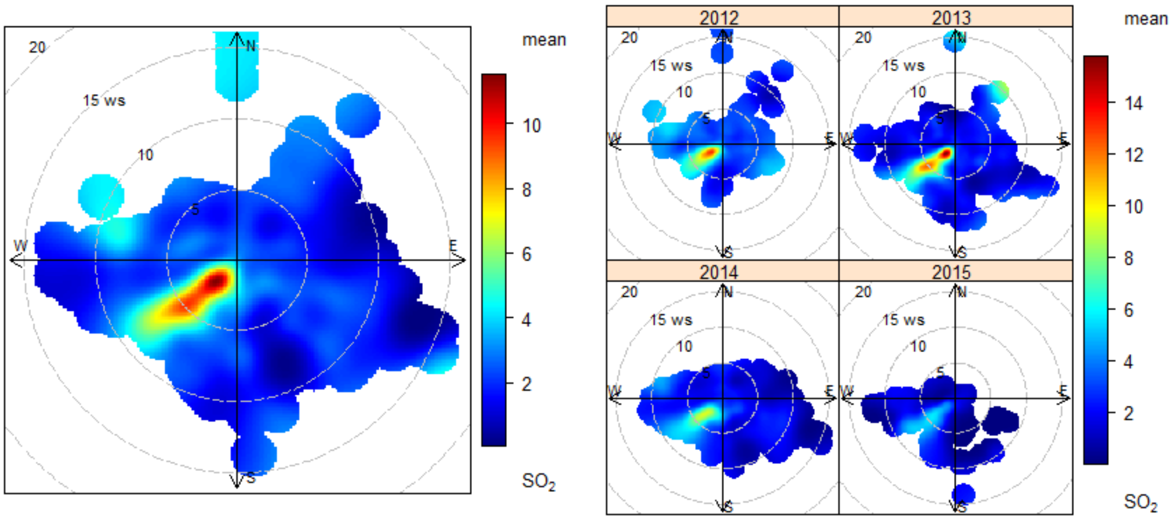


Figure 3.9 Polar Plots and Diurnal of NO_2 Concentrations, Broughty Ferry Road 2016 ($\mu g\ m^{-3}$)

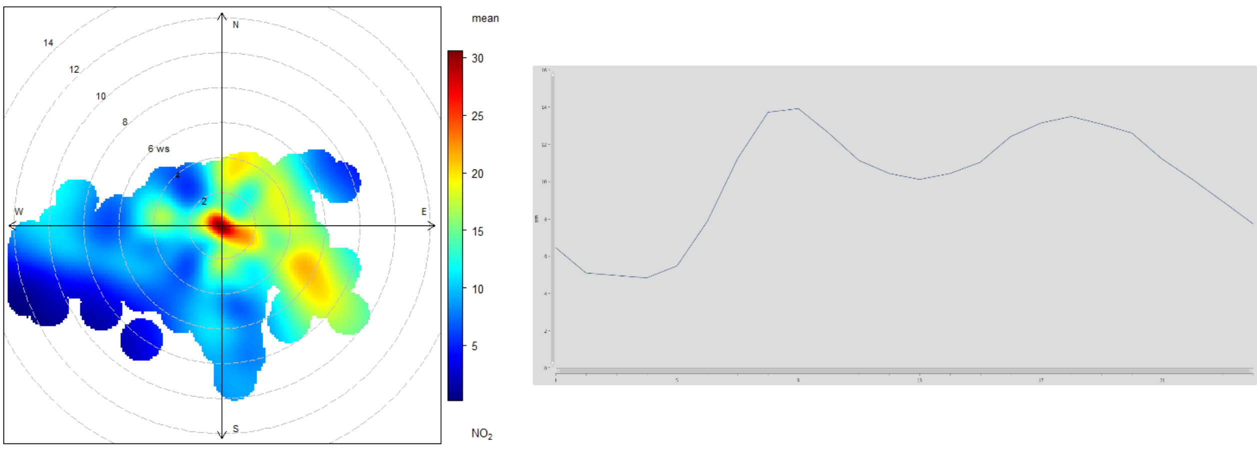


Figure 3.10 Mapped Polar Plots of NO_2 Concentrations at Mains Loan and SO_2 at, Broughty Ferry Road Monitoring Sites (µg m[3])

3.2.2 Particulate Matter – PM_{10}

Table 3.12 summarises the influence of factors on PM_{10} concentrations at Mains Loan and Broughty Ferry Road and Stannergate monitoring sites. At Broughty Ferry Road and Mains, wind direction is a dominating influence on PM_{10} concentrations with an influence of 26.7 and 18.8%, respectively. This together with the polar plots in Figures 3.11 and 3.12 indicates that there is a source being measured at these two sites; and that the source is the same for both sites, located between 95° and 135° relative to the sites, and at 190° to 260°. Wind speed also has an influence on PM_{10} concentrations, with the highest concentrations measured greater than 10 ms^{-1} (22 mph) indicating that the source is not close to the sites.

There is also a clear influence of ambient temperature on PM_{10} concentrations at Broughty Ferry Road and Mains Loan, with concentrations increasing at low temperatures where you would expect lower wind speeds resulting in poor dispersion, and at higher temperatures, when the conditions are drier (Appendix 1, Figures A1.2, A1.4 and A1.5). At both sites, slightly higher PM_{10} concentrations are measured Monday to Friday relative to the weekend, indicating that road traffic is likely to contribute to the total PM_{10} mass. Although, the influence of weekday and hour of the day is much lower than that of wind direction and ambient temperature. This shows that road traffic contributes less to the total PM_{10} than other sources at these two sites.

For PM_{10} at Stannergate the main factors influencing concentrations are the underlying trend, ambient temperature and hour of the day. The hours of the day diurnal plot shows a typical traffic-related pattern, with the highest concentrations measures at 8 am and 6 pm (Figure A1.6, Appendix 1). This is also mirrored in the weekday plot where increased PM_{10} concentrations are measure Monday to Friday. The analysis also shows that PM_{10} concentrations increase with increasing ambient temperature and at lower wind speeds. Together with diurnal and weekly pattern, this indicates that traffic, which could include resuspension of dust from the road surface and diffuse emissions from activity sat the port, are potential sources at Stannergate. An increase in concentrations is also seen at higher wind speed which shows that there is a source of PM further afield. This also ties in with the increasing temperature when you would expect the ground is drier with the higher wind speed causing resuspension of dust.

The unchanging trend in PM_{10} concentrations at Stannergate also indicate that there are additional sources of PM_{10} to what is seen at Broughty Ferry Road and Mains Loan where a decreasing trend is seen. From Figure 3.14, the polar plot shows increased PM_{10} at Stannergate is measured when relatively strong wind (10 – 15 ms^{-1}) is from the east south east at approximately 100° where Dundee Docks and the Firth of Tay are located. The plot also confirms that elevated concentrations are also seen at lower wind speeds with a wind from approximately 85° where the A930 is located relative to the site.

Figure 3.15 maps the polar plots for the three sites. As can be seen from the map and from the polar plots in Figures 3.11 to 3.14, all sites shown a similar profile with increased PM_{10} concentration measured when the wind is from 85° to 135°, and at 190° to 260°. wind speeds of 8 to 15 ms^{-1}. This indicates that here is a common source contributing to PM_{10} concentrations the three sites. The Dundee Ports/Harbour is located to the south of all three sites and deals with dry bulk goods, which could be a source of PM_{10}.

In addition to Dundee Port, Sea salt may also be a significant contributing factor at all three monitoring sites. A study carried out in 2003 (Y. Qin, K. Oduyemi, 2003)[1] suggested that marine aerosols contributed and average of 19.8% (up to 42.3%) of the total PM_{10} mass during a six-month monitoring survey at Abertay University. The influence of high wind speeds and the wind direction resulting in increased PM_{10} concentrations could also be an indicator that this is the case. The study also suggested that the European continent is a major source for secondary pollution species measured in Dundee which is likely to be a contributing factor to the increased concentrations at all sites when the wind is from the east resulting in the similar polar plots.

[1] Y. Qin, K. Oduyemi, Chemical composition of atmospheric aerosol in Dundee, UK, In Atmospheric Environment, Volume 37, Issue 1, 2003, Pages 93-104, ISSN 1352-2310, https://doi.org/10.1016/S1352-2310(02)00658-1. (http://www.sciencedirect.com/science/article/pii/S1352231002006581)

Figures 3.11 to 3.14 also show the annual variation in polar plots for Mains Loan, Broughty Ferry Road and Stannergate. From these figures it can be seen that the sources of PM_{10} have not changed significantly between 2012 and 2016. Although, they highlight that the highest hourly PM_{10} concentrations were experienced during 2015 when the wind was from the south east at a speed of 10 ms^{-1} or greater.

Table 3.2 Modelled Influence of Factors on SO_2 and PM_{10} Concentrations at Broughty Ferry Road

Factor	Influence on PM_{10} Concentrations, Mains Loan (TEOM)	Influence on PM_{10} Concentrations, Broughty Ferry Road (TEOM)	Influence on PM_{10} Concentrations, Broughty Ferry Road (Osiris)	Influence on PM_{10} Concentrations, Stannergate (Osiris)
Ambient Temperature	18.8%	12.3%	13.6%	16.0%
Hour of the Day	5.5%	8.1%	6.4%	14.8%
Rainfall	0.7%	0.9%	1.0%	1.1%
Trend	20.5%	18.9%	20.2%	19.7%
Week of the Year	10.9%	12.4%	12.9%	11.4%
Weekday	10.8%	10.9%	11.4%	13.2%
Wind Direction	18.8%	26.7%	24.5%	13.2%
Wind Speed	14.0%	9.7%	10.0%	10.5%

Figure 3.11 Polar Plots of PM_{10} Concentrations, Mains Loan ($\mu g\,m^{-3}$)

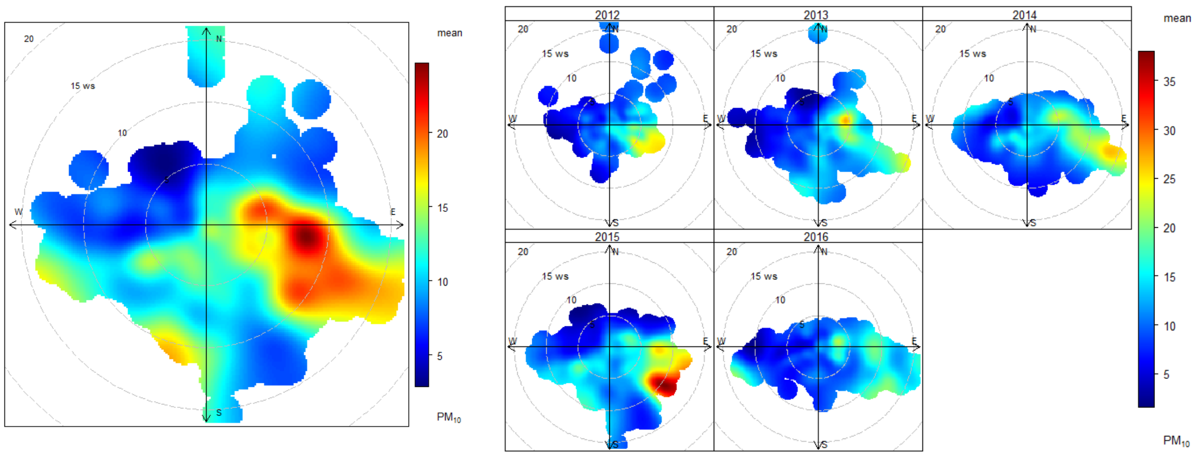


Figure 3.12 Polar Plots of PM_{10} (TEOM) Concentrations, Broughty Ferry Road ($\mu g\,m^{-3}$)

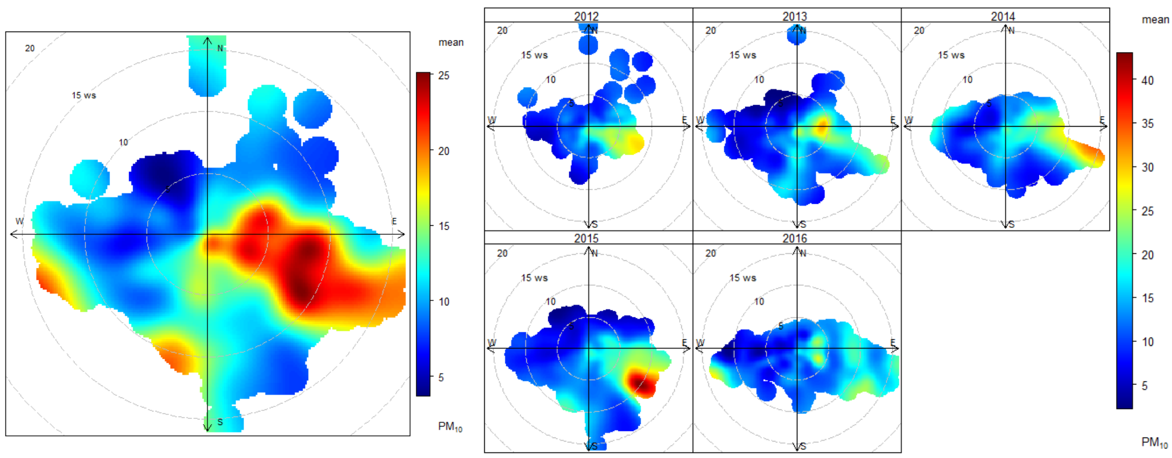
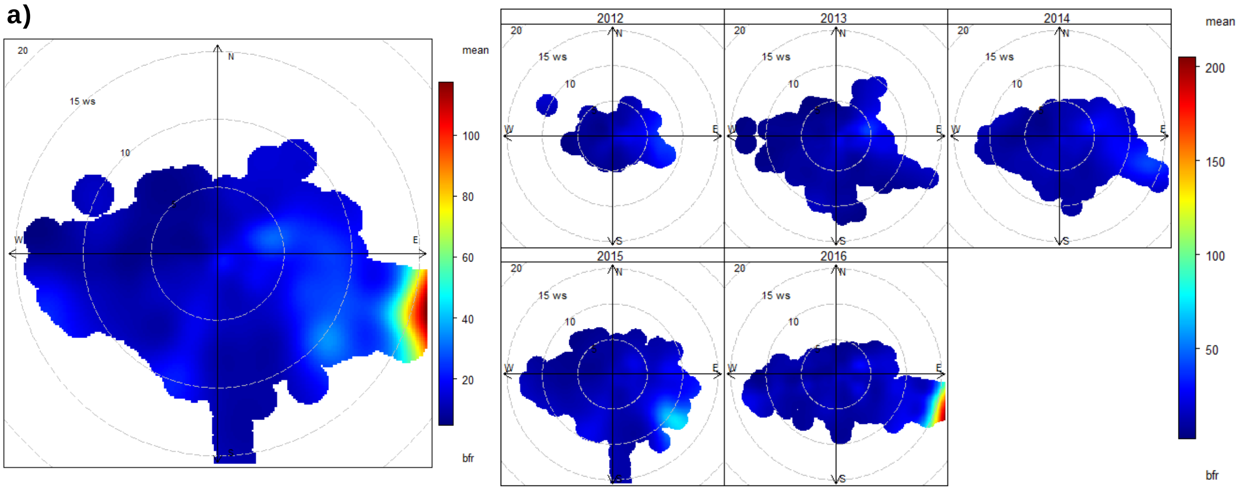


Figure 3.13 Polar Plots of PM_{10} (Osiris) Concentrations, Broughty Ferry Road ($\mu g\ m^{-3}$); a) containing all data; b) with PM_{10} > 100 $\mu g\ m^{-3}$ removed

a)



b)

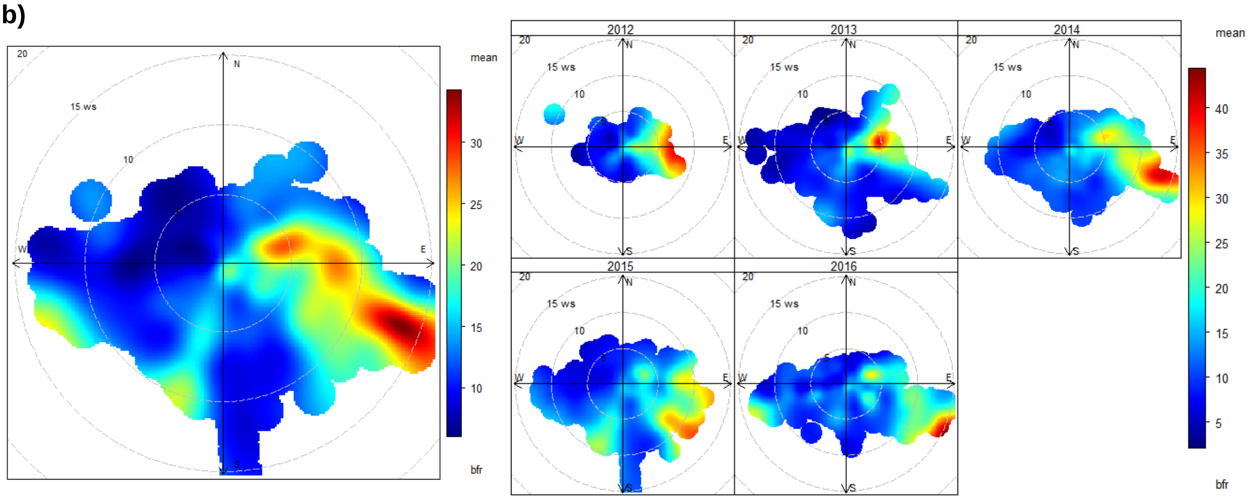


Figure 3.14 Polar Plots of PM_{10} (Osiris) Concentrations, Stannergate ($\mu g\ m^{-3}$)

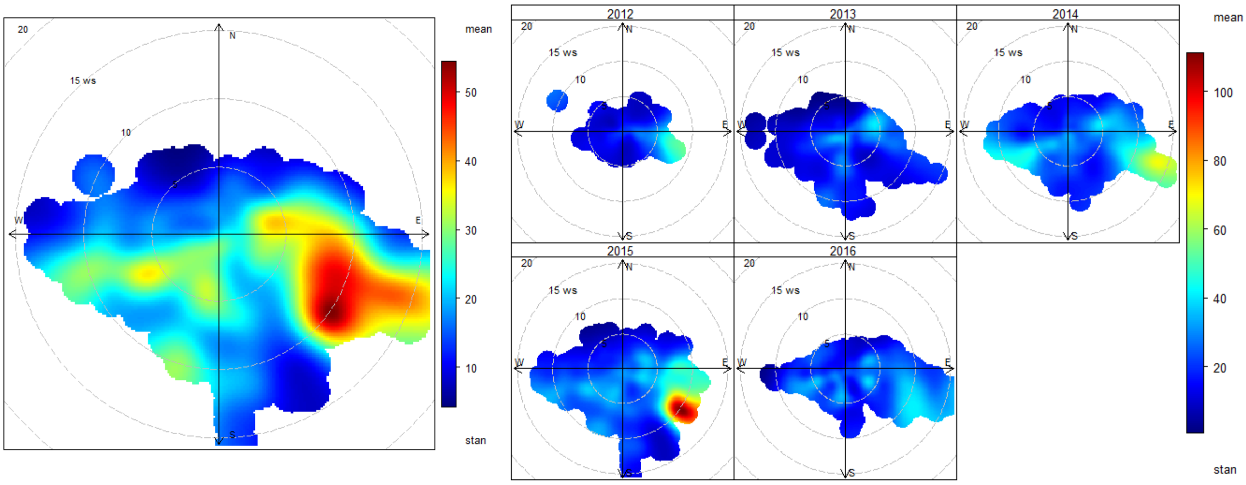
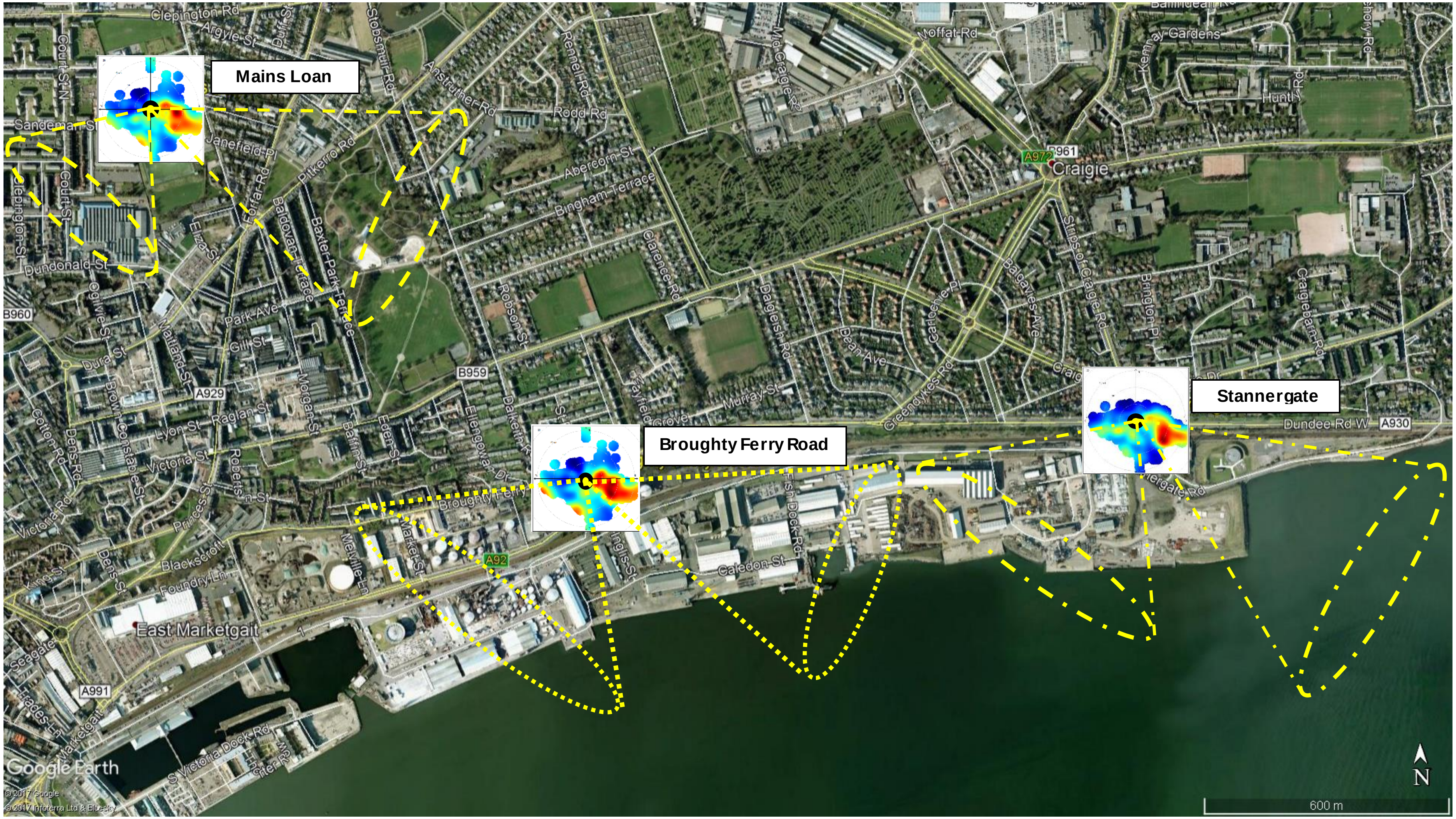


Figure 3.15 Mapped Polar Plots of PM_{10} Concentrations at Mains Loan, Broughty Ferry Road and Stannergate Monitoring Sites (µg m[3])



4 Conclusions

Ricardo Energy & Environment have been contracted by Dundee City Council to investigate trends in particulate matter (PM_{10}), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) concentrations during 2012 to 2016 at the following three air quality monitoring sites in Dundee: Dundee Broughty Ferry Road (SO_2 and PM_{10}), Dundee Mains Loan (NO_2 and PM_{10}) and Dundee Stannergate (PM_{10}). The study aims to provide Dundee City Council with an assessment of potential sources and changes in pollutant concentrations and at these sites.

Two aspects of the data were investigated in the study: the trends in pollutant concentrations and the location of potential sources resulting in increased pollutant concentrations. The statistical software 'R' (https://www.r-project.org/) and the openair package (http://www.openair-project.org/) was used to carry the analysis. A machine learning technique, 'boosted regression trees', was used for these analyses. This technique provided information on pollutant concentration trends with the effects of meteorology removed ('deweathered') to provide a more accurate picture of the trends. In addition, information was gained regarding eight factors and their relative influences on n pollutant concentrations. Polar plots were then used to then investigate potential sources.

Trends in Pollutant Concentrations

The results indicate that deweathered NO_2 concentrations remain unchanged during 2012 to 2016 at Mains Loan whilst a statistically significant decreasing trend in PM_{10} concentrations can be seen. When compared to the trends seen in the unadjusted measurement data, both the modelled and measured trends in NO_2 and PM_{10} agree.

Deweathered SO_2, PM_{10} (TEOM) and PM_{10} (Osiris) concentrations show a statistically significant decreasing trend during 2012 to 2016. When compared to the trends seen in the unadjusted measurement data, both the modelled and measured trends in SO_2 and PM_{10} agree.

In contrast to the trends at Broughty Ferry Road and Mains Loan, the deweathered trend in PM_{10} concentrations at Stannergate have no statistically significant trend during 2012 to 2016 with levels remaining relatively unchanged. When compared to the trends seen in the unadjusted measurement data, both the modelled and measured trends in PM_{10} agree.

Pollutant Sources – Gaseous Pollutants

- The highest SO_2 concentrations were measured when the wind is from the south west, where an oil refinery is located.

- Maximum NO_2 concentrations at Broughty Ferry Road and Mains Road were measured with low wind speeds. The diurnal plots also show to that that road traffic is the main source of NOx at these sites.

Pollutant Sources – PM_{10}

- Similar polar plot profiles were seen at all sites with increased PM_{10} concentrations seen when the wind was from 95° to 135°, and from 190° to 260°, where 360° is north indicating that here is a common source contributing to PM_{10} concentrations the three sites.

- The Dundee Ports/Harbour is located to the south of all three sites and deals with dry bulk goods, which could be a source of PM_{10}.

- Wind speed also has an influence on PM_{10} concentrations at all sites, with increased concentrations measured at wind speeds close to 0 ms^{-1} and greater than 10 ms^{-1} (22 mph) indicating that the source of increased PM_{10} is not local to the sites.

- The annual variation in polar plots for Mains Loan, Broughty Ferry Road and Stannergate. show that the sources of PM_{10} have not changed significantly between 2012 and 2016.

- The difference trend in PM_{10} concentrations at Stannergate indicate that there are additional sources of PM_{10} with increased concentrations measured when relatively strong wind (10 – 15 ms^{-1}) is from the east south east at approximately 100° where Dundee Docks and the Firth of Tay are located.

- Elevated concentrations at Stannergate are also seen at lower wind speeds with a wind from approximately 85° where the A930 is located relative to the site.

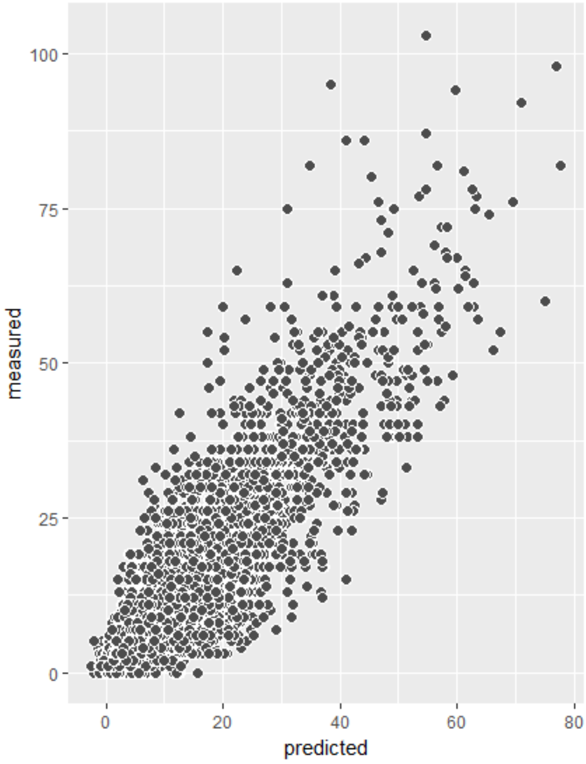
- Sea salt may also be a significant contributing factor at all three monitoring sites (Y. Qin, K. Oduyemi, 2003) - the influence of high wind speeds and the wind direction resulting in increased PM_{10} concentrations is an indicator that this is the case.

- An earlier study (Y. Qin, K. Oduyemi, 2003) also suggested that the European continent is a major source for secondary pollution species measured in Dundee which is likely to be a contributing factor to the increased concentrations at all sites when the wind is from the east.

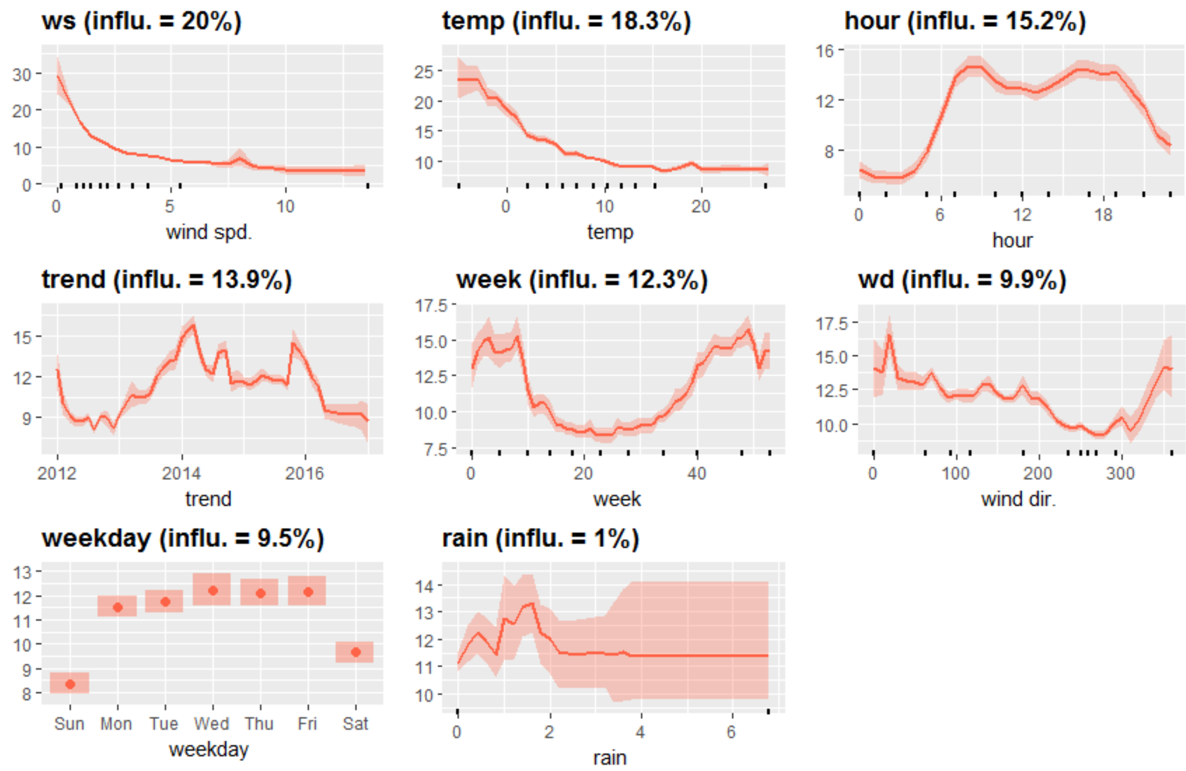
Appendices

Appendix 1 – Model Results

Figure A1.1 Mains Loan Model Performance, Influence of Factors and Deweathered Time Series for NO_2



statistic	value
n	7455.00
FAC2	0.79
MB	-0.06
MGE	3.67
NMB	-0.01
NMGE	0.33
RMSE	5.57
r	0.88
COE	0.54
IOA	0.77



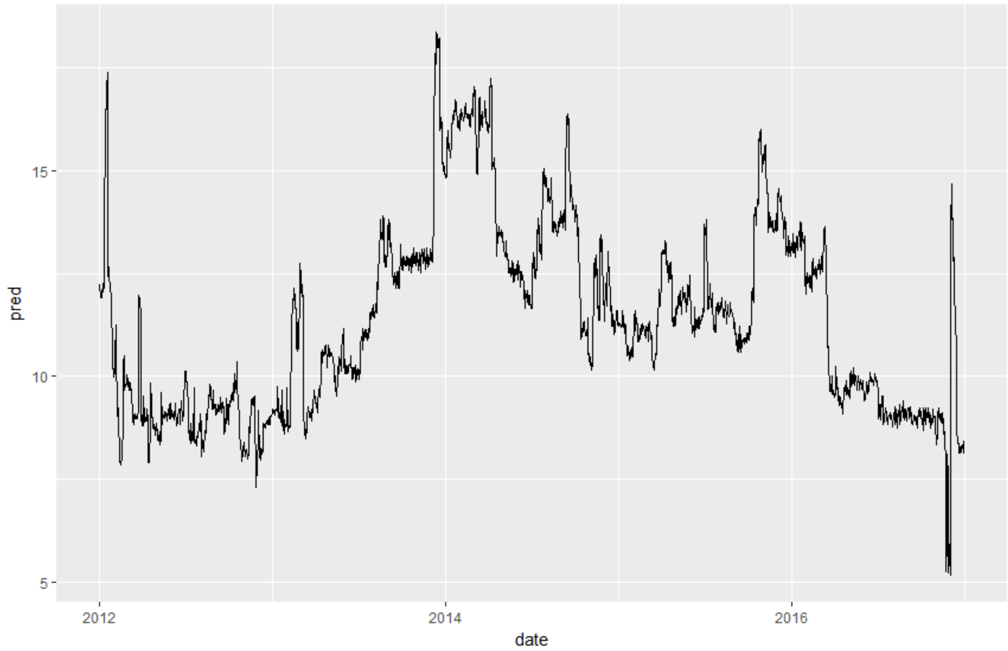
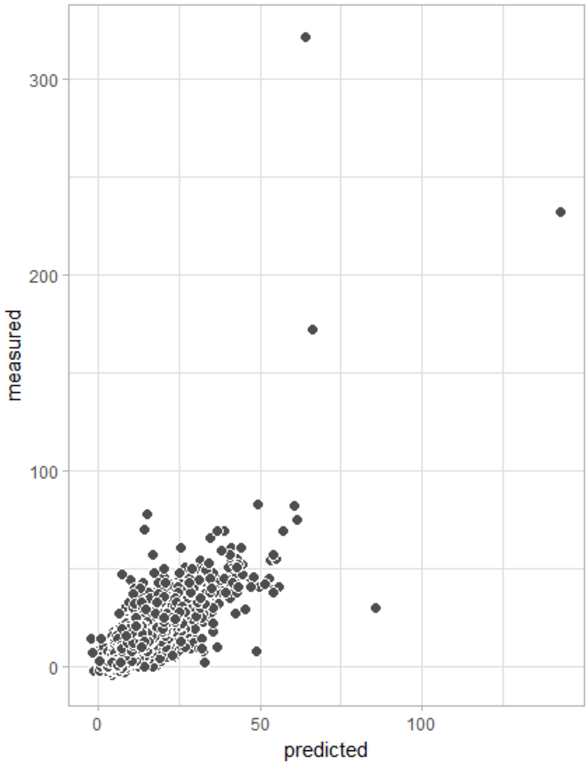
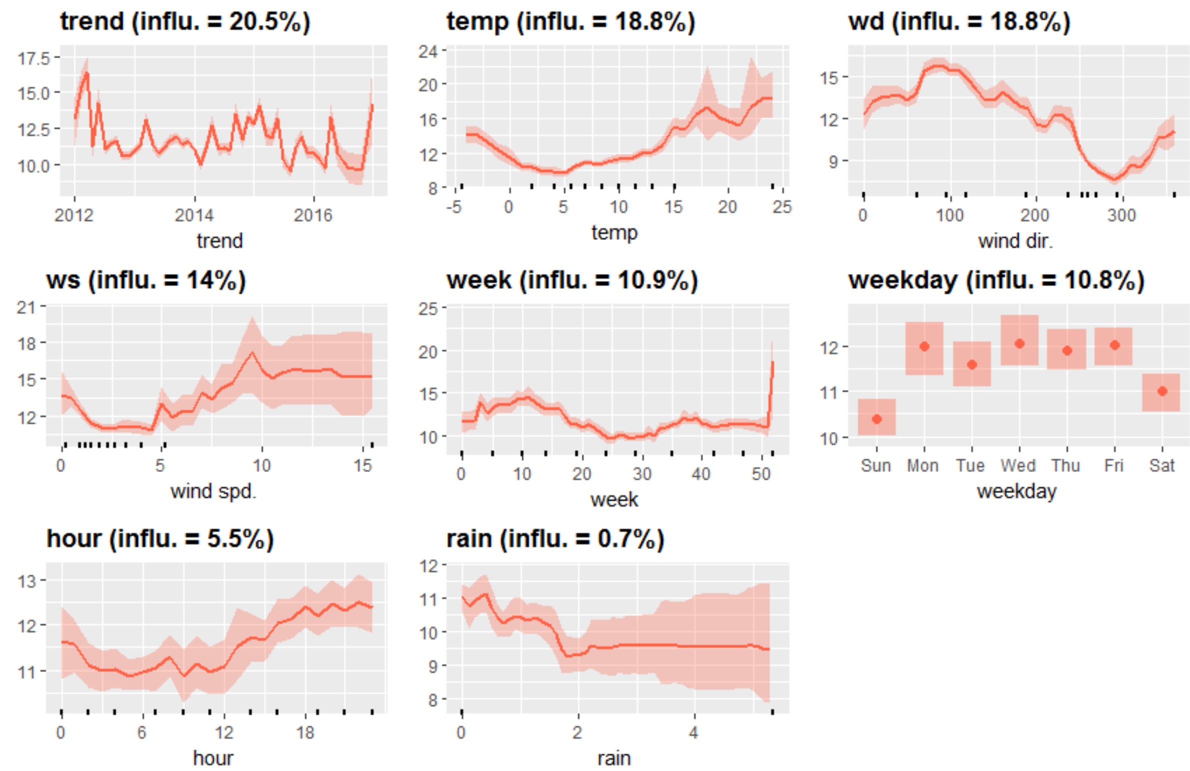


Figure A1.2 Mains Loan Model Performance, Influence of Factors and Deweathered Time Series for PM_{10}



statistic	value
n	7945.00
FAC2	0.84
MB	-0.03
MGE	3.86
NMB	0.00
NMGE	0.33
RMSE	6.22
r	0.76
COE	0.36
IOA	0.68


trend (influ. = 20.5%)
temp (influ. = 18.8%)
wd (influ. = 18.8%)
ws (influ. = 14%)
week (influ. = 10.9%)
weekday (influ. = 10.8%)
hour (influ. = 5.5%)
rain (influ. = 0.7%)
trend
temp
wind dir.
wind spd.
week
weekday
hour
rain
Sun Mon Tue Wed Thu Fri Sat

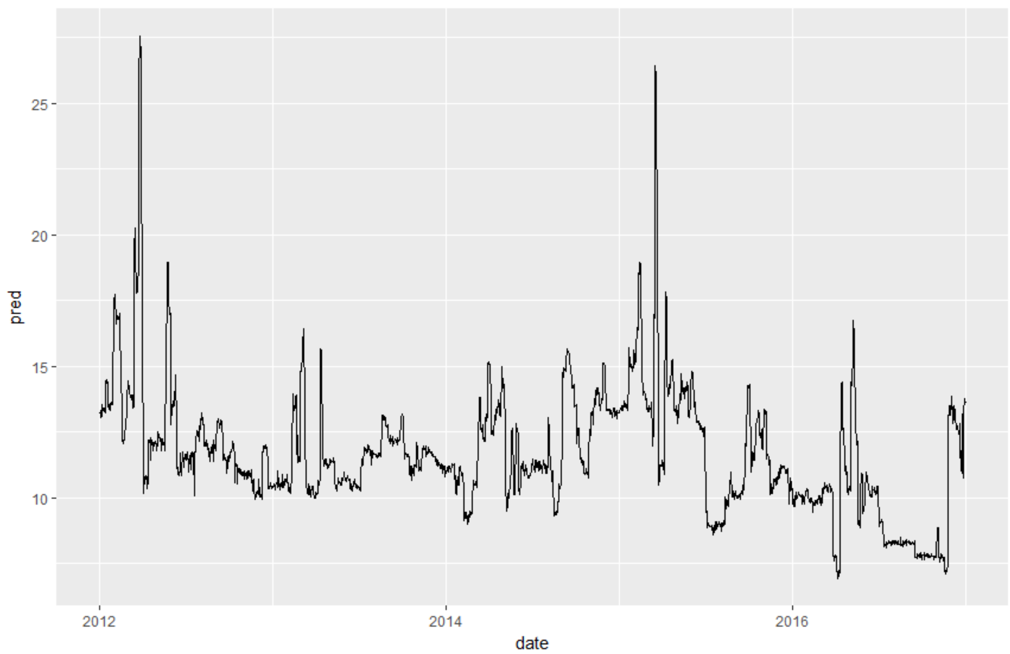
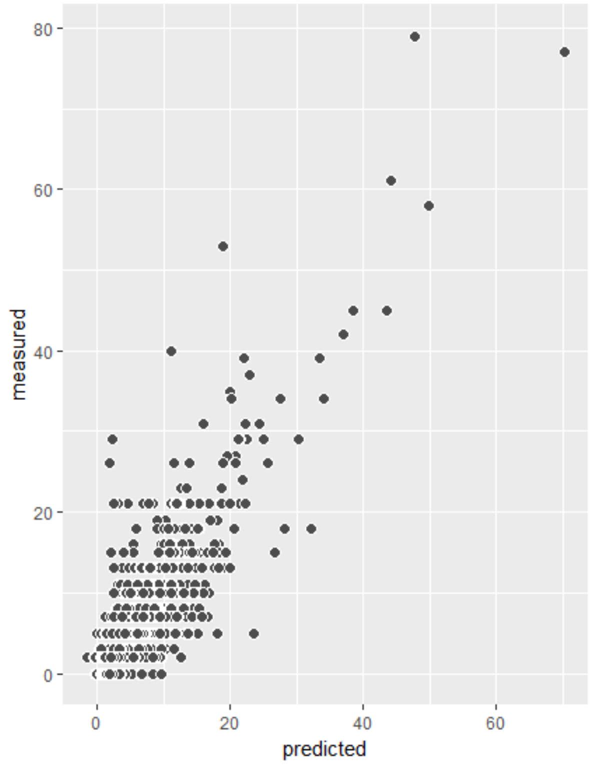
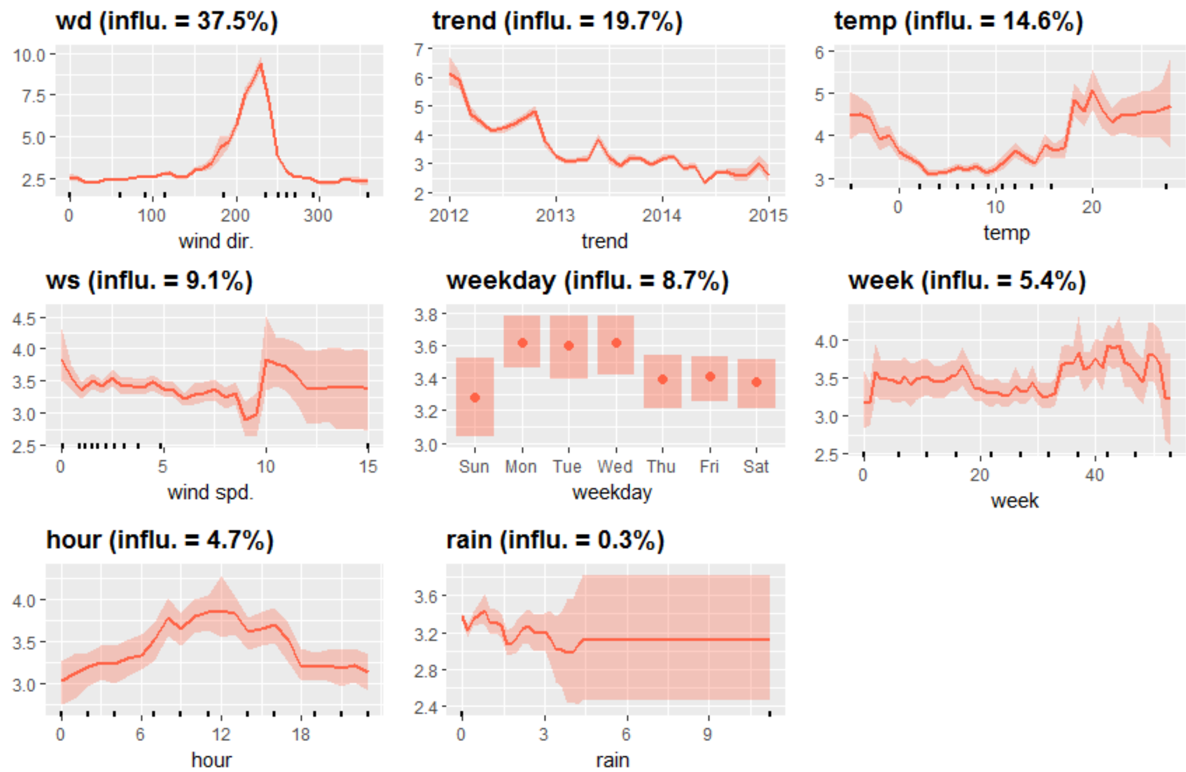

pred
date
2012
2014
2016

Figure A1.3 Broughty Ferry Road Model Performance, Influence of Factors and Deweathered Time Series for SO_2



statistic	value
n	5009.00
FAC2	0.78
MB	0.03
MGE	1.35
NMB	0.01
NMGE	0.38
RMSE	2.33
r	0.84
COE	0.44
IOA	0.72



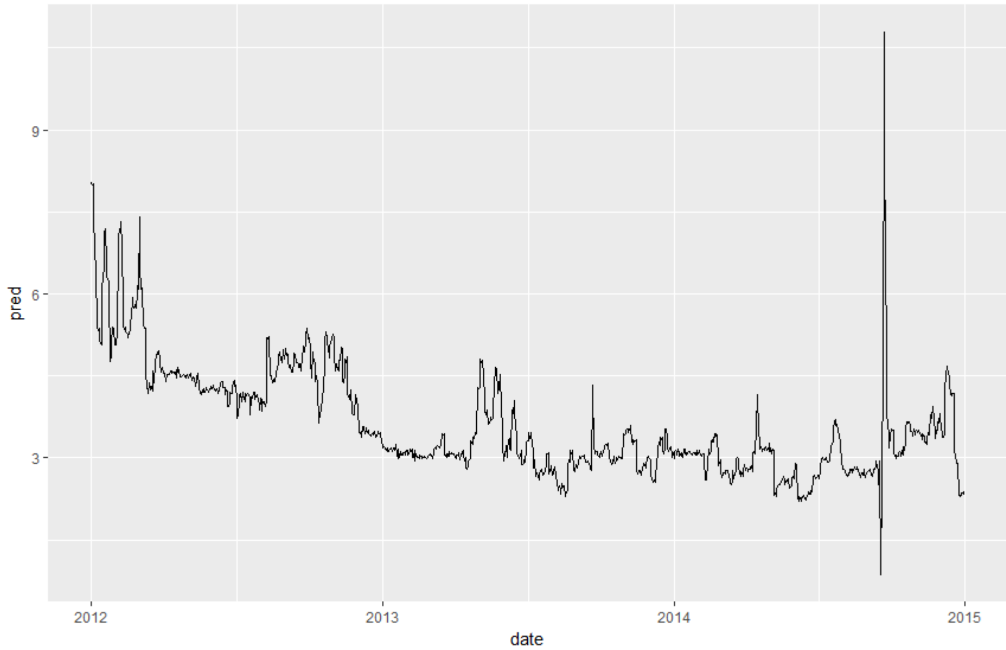
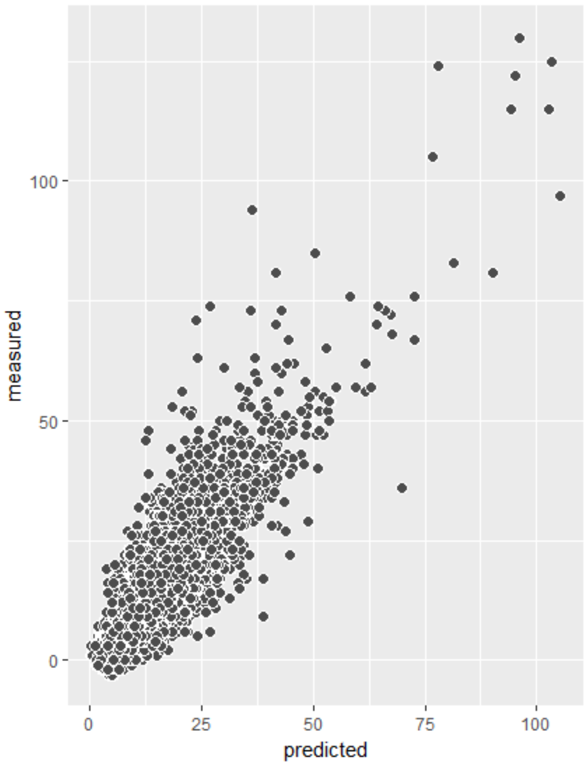
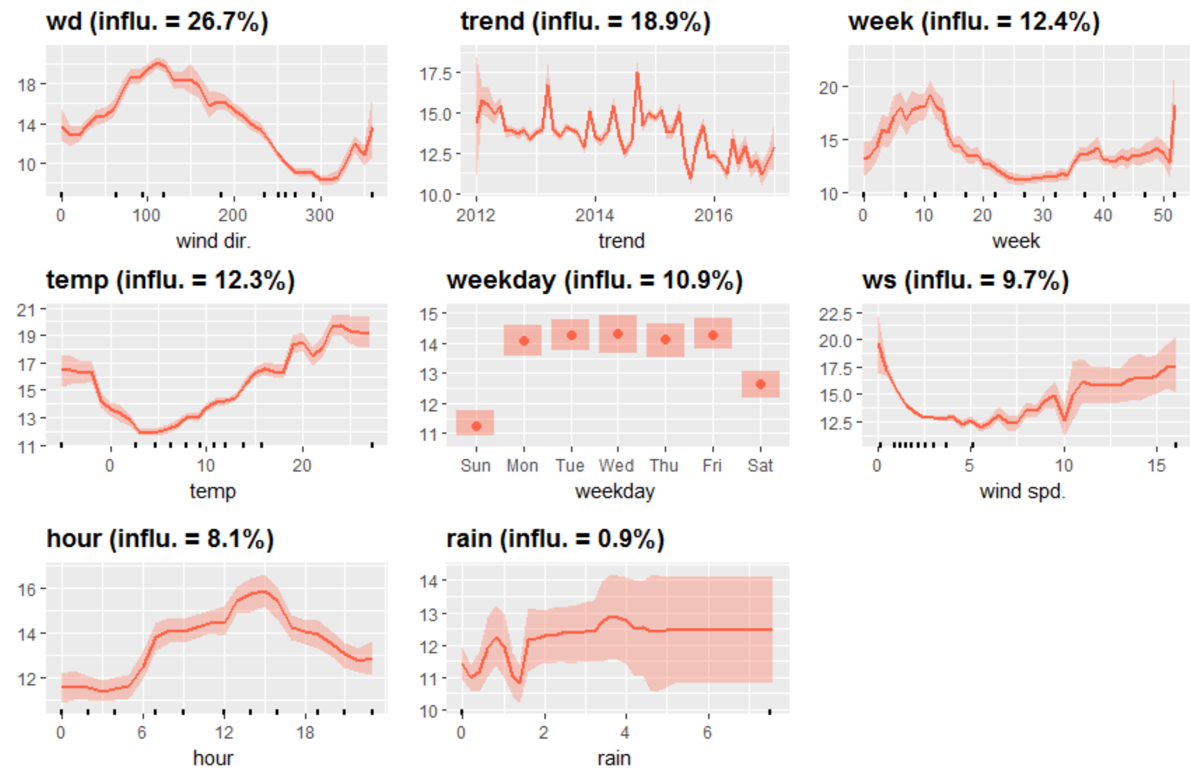


Figure A1.4 Broughty Ferry Road Model Performance, Influence of Factors and Deweathered Time Series for PM_{10} (TEOM)



statistic	value
n	8234.00
FAC2	0.88
MB	-0.05
MGE	3.78
NMB	0.00
NMGE	0.28
RMSE	5.31
r	0.86
COE	0.48
IOA	0.74


wd (influ. = 26.7%)
wind dir.
trend (influ. = 18.9%)
trend
week (influ. = 12.4%)
week
temp (influ. = 12.3%)
temp
weekday (influ. = 10.9%)
Sun
Mon
Tue
Wed
Thu
Fri
Sat
weekday
ws (influ. = 9.7%)
wind spd.
hour (influ. = 8.1%)
hour
rain (influ. = 0.9%)
rain

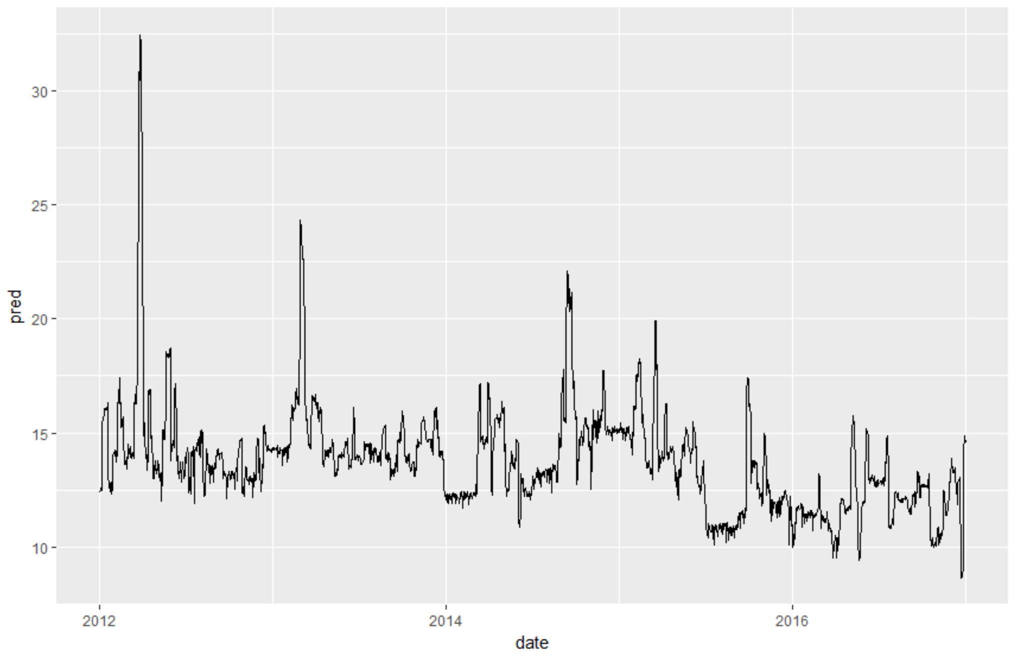
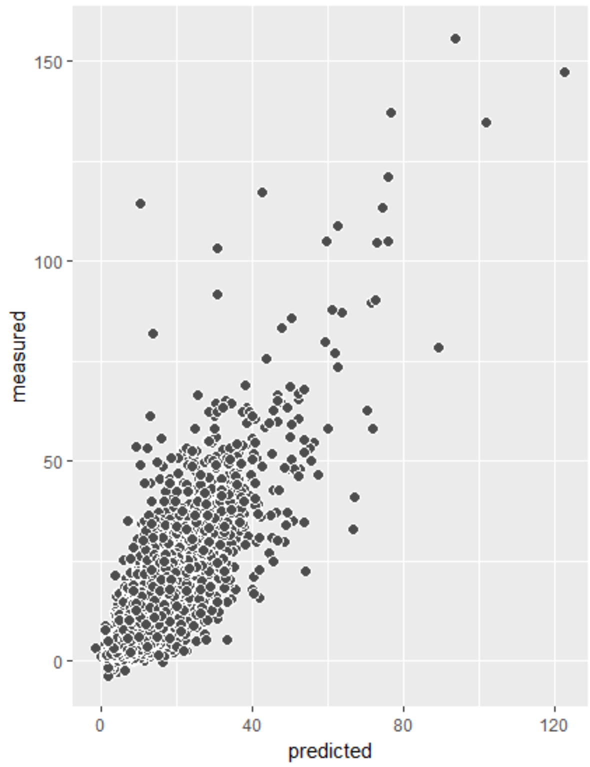
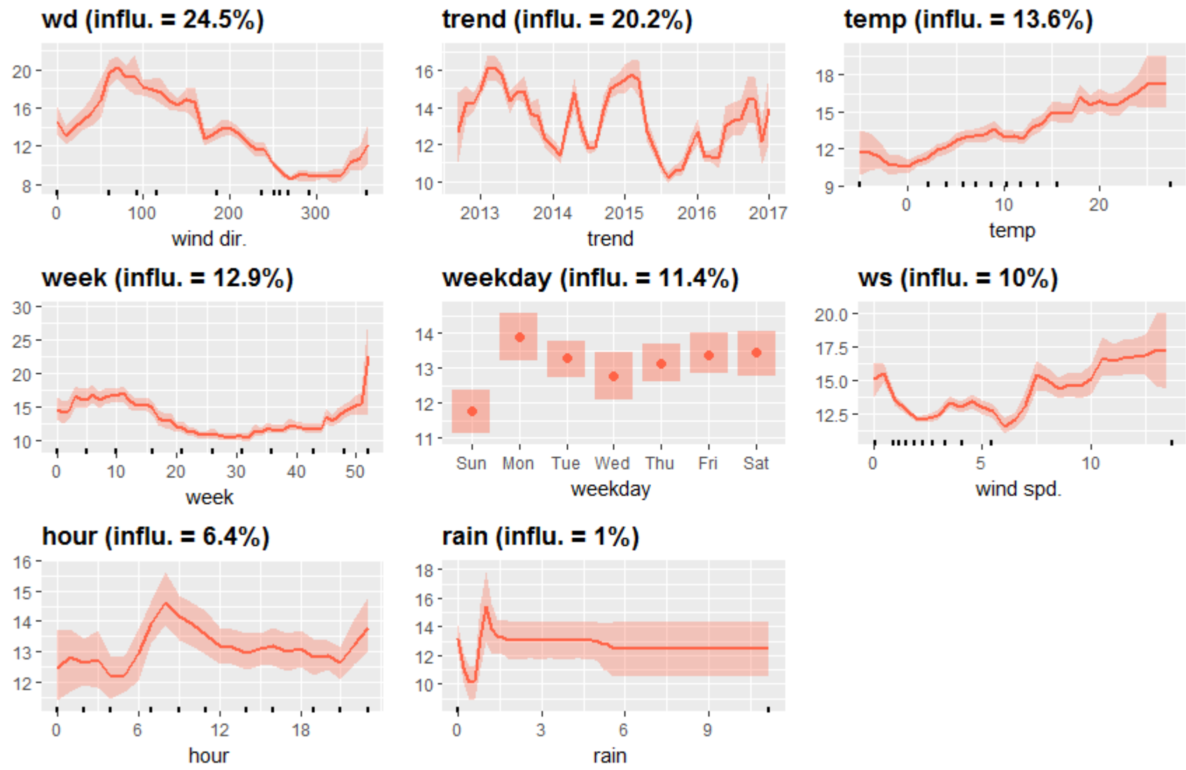

pred
date

Figure A1.5 Broughty Ferry Road Osiris Model Performance, Influence of Factors and Deweathered Time Series for PM_{10}



statistic	value
n	6494.00
FAC2	0.83
MB	-0.16
MGE	4.58
NMB	-0.01
NMGE	0.35
RMSE	6.96
r	0.81
COE	0.41
IOA	0.71



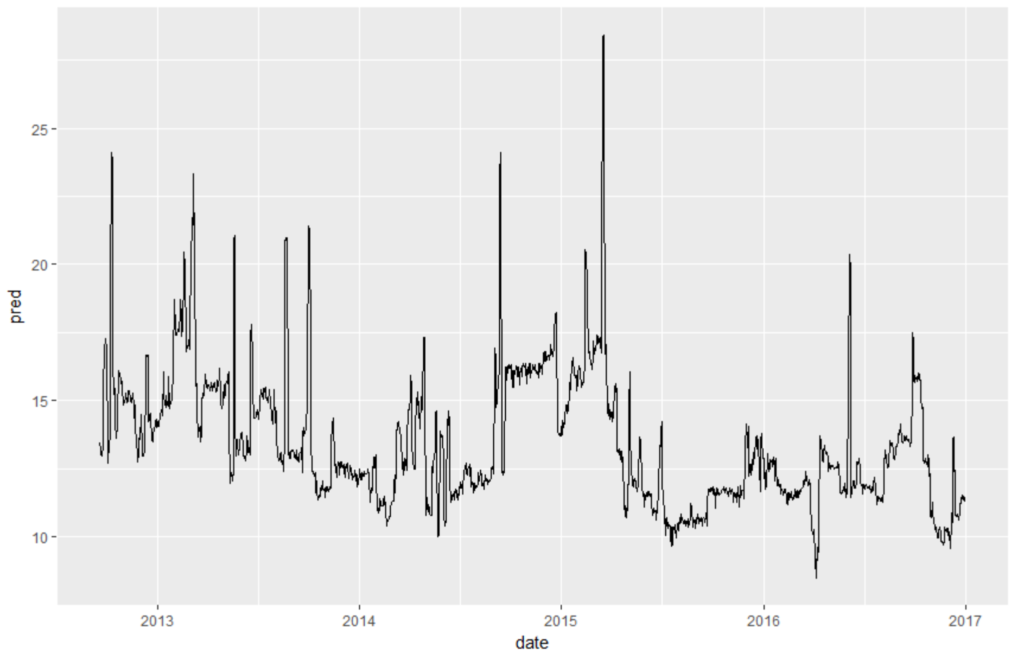
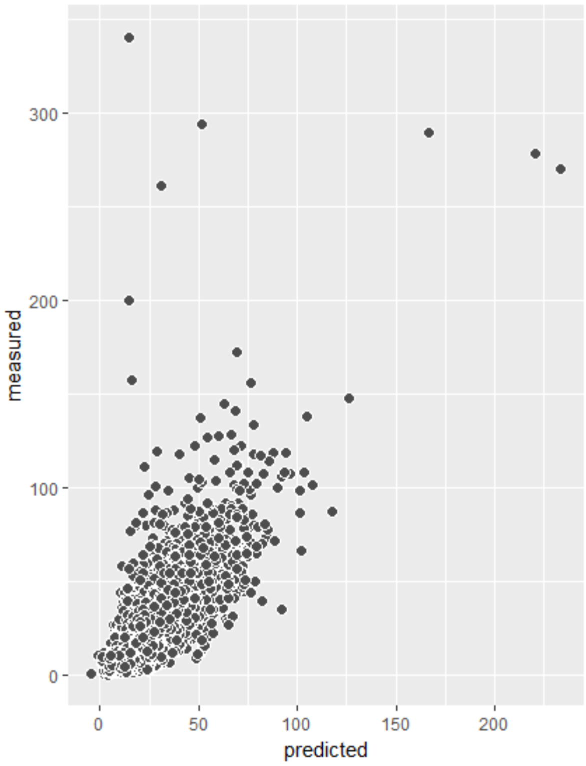
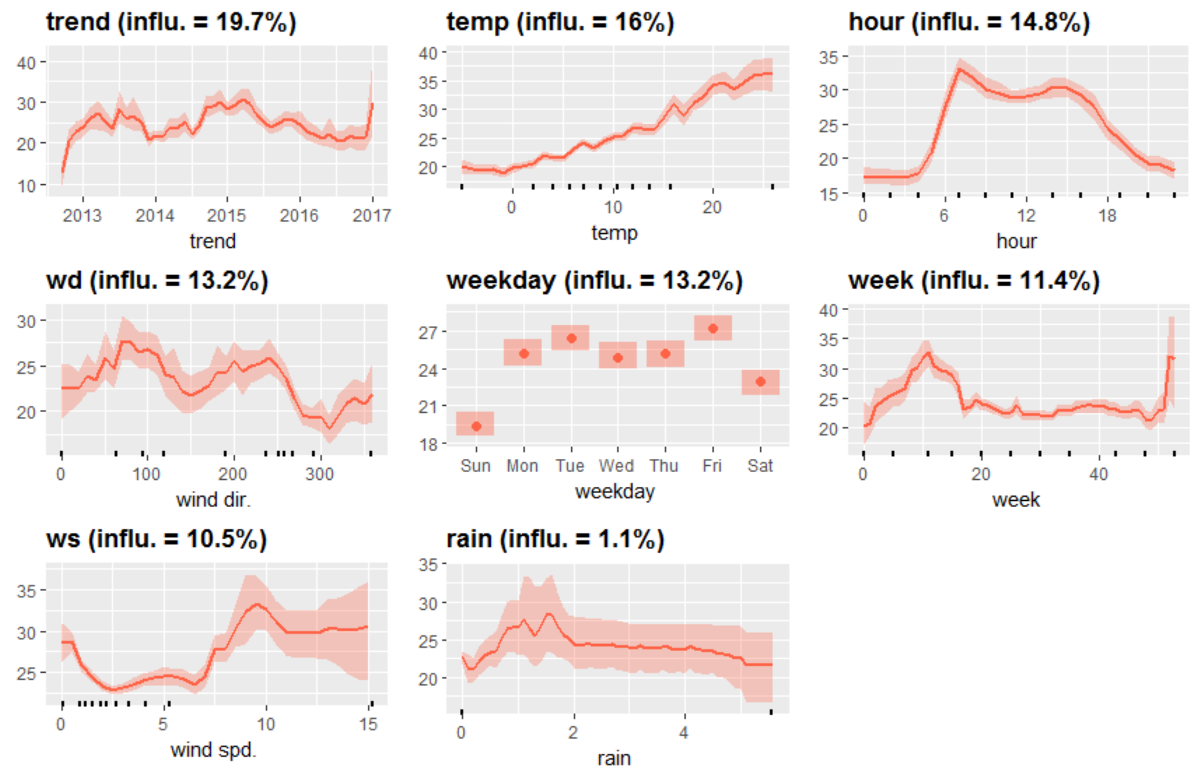
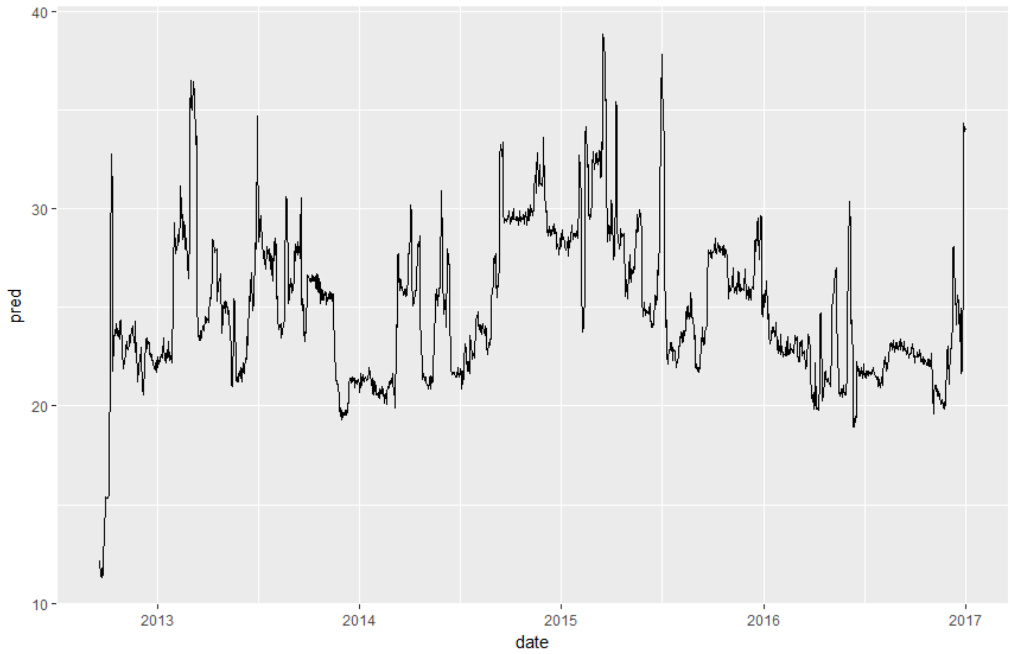


Figure A1.6 Stannergate Osiris Model Performance, Influence of Factors and Deweathered Time Series for PM_{10}

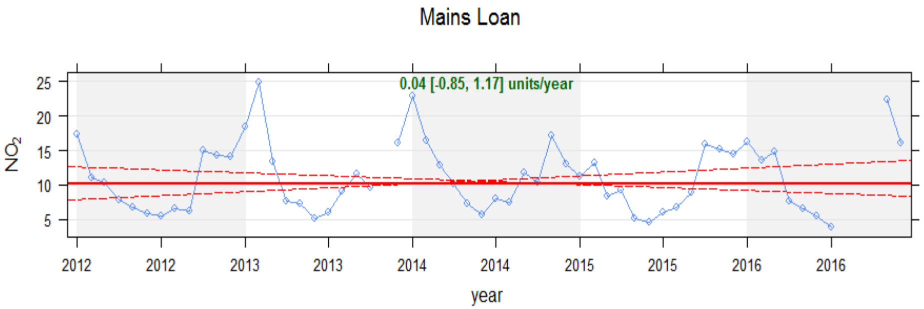


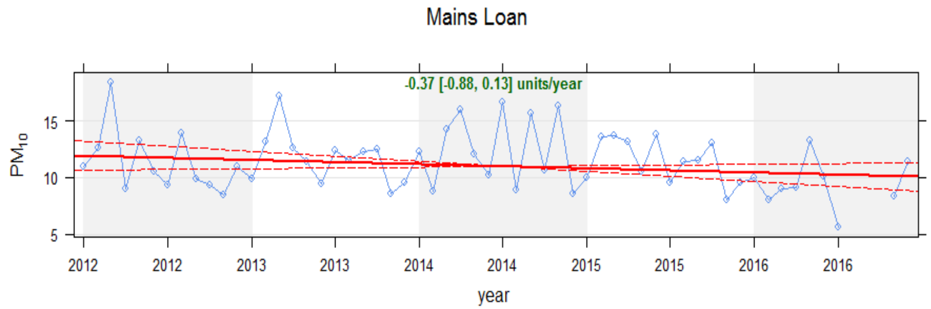
statistic	value
n	6472.00
FAC2	0.87
MB	0.11
MGE	7.63
NMB	0.00
NMGE	0.32
RMSE	12.75
r	0.76
COE	0.41
IOA	0.70

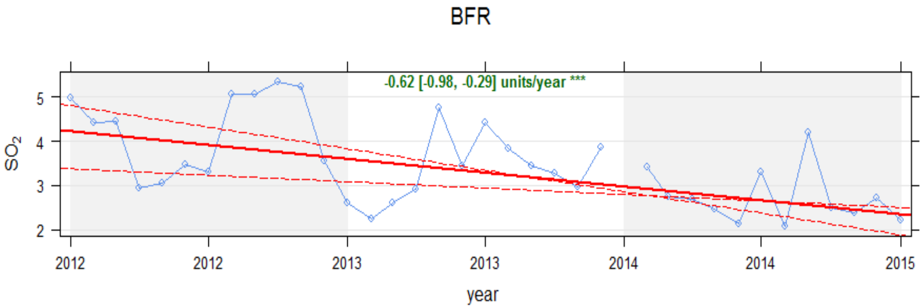

trend (influ. = 19.7%)
trend
temp (influ. = 16%)
temp
hour (influ. = 14.8%)
hour
wd (influ. = 13.2%)
wind dir.
weekday (influ. = 13.2%)
Sun Mon Tue Wed Thu Fri Sat
weekday
week (influ. = 11.4%)
week
ws (influ. = 10.5%)
wind spd.
rain (influ. = 1.1%)
rain

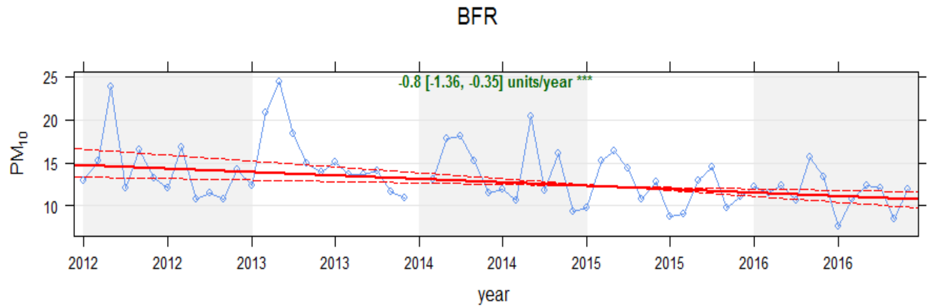

pred
date

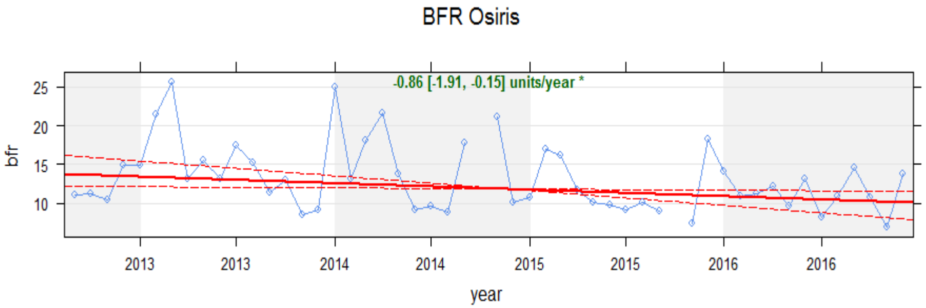
Appendix 2 – Trends Derived Using Unadjusted Measurement Data

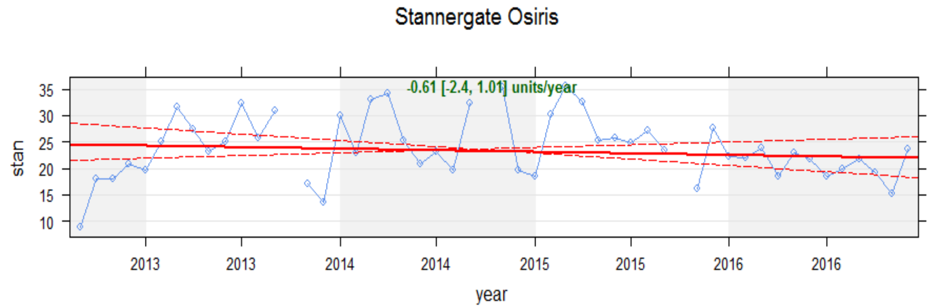












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