Analysis of air pollution in North Lincolnshire

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version: 21st January 2009

Contents

1 Introduction

1.1 Background and aims

North Lincolnshire, particularly the area around Scunthorpe, represents a complex industrial location characterised by a wide range of large scale emitting processes in close proximity to a large population. North Lincolnshire Council, as any other Local Authority, are concerned with safeguarding public health by reducing exposure to harmful air pollutant concentrations through the process of Local Air Quality Management (LAQM). In completing this formal process Local Authorities would benefit from the use of structured air quality tools that promote the focus of effort on controlling those specific polluting processes that will have the maximum impact at the minimal cost. Such tools would be capable of:

- confidently identify specific sources and assess their relative importance (source identification/apportionment);
- assessing trends in air pollution over time to demonstrate successful policy measures or determining whether the impact of an emitting process is worsening over time. Of most significance would be a means of removing the variation due to meteorology so that 'true' trends could be seen rather than those that have been masked or over-emphasised by different weather conditions.

This document summarises the analysis of air pollution at a network of air pollution monitoring sites in North Lincolnshire. This work represents a collaboration between the University of Leeds and AEA to develop a case study for the insightful analysis of air pollution data for North Lincolnshire Council. More information of the techniques used can be found in Carslaw and Ropkins (2009).

Note! – newer version of `openair`
Since this report was written (September 2008) there are been many refinements and developments of the **openair** package. The use of many functions has been simplified and additional flexibility added e.g. control over colours used for plotting surfaces and automatic formatting of units such as µg m^{-3}. These additional developments are summarised in the **openair** manual and will be covered in the North Lincs tutorial.

The main purpose of this document is to show how the **openair** package is applied to a complex source location. There are a myriad of ways in which the data can be analysed and this report can only consider a subset. However, it is written in such a way that North Lincolnshire Council can reproduce the analyses used as well as considering new ones. The vast bulk of the analysis contained in this report can be reproduced easily. Sometimes, however, we also illustrate other useful data manipulation techniques using R. It is recommended that this document should be read in conjunction with the evolving documentation for the **openair** tools Carslaw and Ropkins (2009). The documentation provides extensive example of the tools as well a descriptions of option available controlling their use. In early 2009, a website will be made available where the package, documentation and other information will be made available. Also, the tools themselves will be documented in the **openair** package.

2 North Lincolnshire monitoring network

The North Lincolnshire air monitoring network has consisted of a total of 16 sites in its history of which 11 sites are still operational in 2008. The majority of the sites are located around the town of Scunthorpe, concentrating in the vicinity of the integrated steelworks run by Corus. The site details are presented in Table 1 and include the site name, its period of operation, site classification, the pollutants it measures and the geographical coordinates. The table also includes a map id which relates the site to the location on the map. There is a single site in the network that lies some distance to the east of Scunthorpe near to the coast - this is a South Killingholme and represents concentrations associated with the nearby power station and oil refinery. It is this port that is used to transport in the raw materials for the steelworks.

The central Scunthorpe sites can be confusing, given their operational history. The Scunthorpe site was originally a part of the National network (Automatic Urban and Rural Network, AURN) and measured PM_{10} (by TEOM) and SO_2. The site referred to as Scunthorpe Town NO_X and CO has been treated as a separate site (because these instruments were originally owned and run by the North Lincolnshire Council) but actually refers to different instruments at the same site location. Similarly, the Scunthorpe Town Partisol label refers to the gravimetric Partisol analyser at the same Scunthorpe site. Different site names for specific equipment is not uncommon where a site has been affiliated with the AURN, particularly when the analysers involved have been in operation over different time periods. For this reason, despite being treated as separate sites, the different pollutants here are comparable with one another, provided that they are coincident in time.

Table 1: North Lincolnshire Council monitoring network summary.

ID	Site.Name	Type	East	North	Pollutants	Start	End
1	Scunthorpe	URBAN INDUSTRIAL	490592	410689	PM_{10}, SO_2	15/12/1997	18/03/2004
2	North Lincolnshire Killingholme	URBAN INDUSTRIAL	514879	416137	NO_2, PM_{10}, SO_2	01/03/2003	-
3	North Lincolnshire Keadby	ROADSIDE	483594	411073	NO_2, PM_{10}, SO_2	18/12/2003	15/02/2005
4	Scunthorpe Town	URBAN INDUSTRIAL	490421	410812	NO_2, PM_{10}, SO_2	06/06/2004	-
5	Scunthorpe Town NO_X & CO	URBAN INDUSTRIAL	490421	410812	CO, NO_2	06/06/2004	-
6	Scunthorpe Lincoln Gardens	URBAN BACKGROUND	489490	408910	PM_{10}	30/11/2004	-
7	North Lincolnshire Appleby	URBAN BACKGROUND	494819	414965	NO_2, PM_{10}, SO_2	15/02/2005	25/08/2005
8	Scunthorpe East Common Lane	URBAN BACKGROUND	490662	409791	PM_{10}	01/03/2005	-
9	North Lincolnshire Broughton	URBAN BACKGROUND	496048	409411	PM_{10}	01/03/2005	-
10	Scunthorpe Allanby Street	ROADSIDE	489273	411446	PM_{10}	01/07/2005	-
11	Scunthorpe Kingsway House	ROADSIDE	489146	409888	NO_2	09/08/2005	-
12	North Lincolnshire Santon	URBAN INDUSTRIAL	492945	411931	NO_2, PM_{10}, $PM_{2.5}$, SO_2	01/10/2005	-
13	Scunthorpe Gallagher Retail Park	ROADSIDE	486710	401111	NO_2	24/01/2006	-
14	North Lincolnshire Appleby Village	URBAN BACKGROUND	495081	414761	PM_{10}	07/02/2007	-
15	Scunthorpe Lakeside	URBAN BACKGROUND	491755	408242	PM_{10}	01/04/2006	01/04/2006
16	Scunthorpe Town PARTISOL	URBAN INDUSTRIAL	490421	410812	PM_{10}	01/04/2006	01/04/2006

Figure 1: North Lincolnshire monitoring site locations. Multimap.com, Digital Map Data ©Bartholomew 2003, ©MapSite.com Ltd. All rights reserved.

3 Data

This case study is primarily based on monitoring data gathered from the North Lincolnshire Council's air quality monitoring campaign in addition to some data from the UK's national networks. Some of the more complicated and incisive analysis also benefits from the addition of meteorological data (chiefly from the monitoring sites themselves although in the absence of any formal QA procedure this has been compared with a nearby Met Office met data set). As a result, it is essential in forming robust and meaningful conclusions from the data that the nature of the data is truly appreciated. This section describes some of the specifics of the data and the units used.

3.1 Pollutant data

- All the raw data used in this analysis are GMT hour beginning.
- All pollutants are presented in gravimetric units (at 20 °C and at 1013 mb) and use

μg m^{-3} for all except CO which is presented in mg m^{-3}.

- PM_{10} data is TEOM data which has been adjusted to a gravimetric equivalent using the accepted (but not wholly correct) factor of 1.3. Where genuine gravimetric PM_{10} data is presented (i.e. from the Lakeside, Scunthorpe Town Partisol and High Santon sites), this will be labelled as PM_{10} Partisol data.
- NO_X data is in μg m^{-3} (as NO_2)

3.2 Meteorological data

Not all the gathered met data has been presented in this case study. There may be occasions where analysis has been presented which has been derived using the met data but the met data itself has not been presented. Therefore, a complete list of the met data is presented below with the associated units used.

- Temperature is in °C.
- Wind direction is in ° and wind speed data is in m s^{-1}.
- Rh is relative humidity as a percentage.
- Pressure is in mbar.

All the data used in this report are available in an "R workspace" **north_lincs.RData**. The workspace is a binary file, which in this case contains a number of *data frames* containing the data from North Lincs in a format that can be processed by **openair**. The workspace can be loaded in R by choosing File/Load workspace... The code below shows how to list all the components of the workspace – basically data frames of concentrations and meteorological data. Once loaded, the functions shown in this document can readily be recreated. Most of the names used below should be self explanatory.

```
ls()
 [1] "allanby"              "appleby"            "applebyv"
 [4] "blooms"               "broughton"          "dailymet_scun"
 [7] "date"                 "eastcommon"         "gallagher"
[10] "highsanton"           "keadby"             "killingholme"
[13] "kingsway"             "lakeside"           "lincoln"
[16] "met_kill"             "met_scun"           "prepare"
[19] "santon"               "scunthorpe"         "scunthorpet"
[22] "scunthorpet_noxco" "scunthorpet_partisol"
```

More details can be found in the main documentation Carslaw and Ropkins (2009), but to view the first few lines of the data frame **santon**, type

```
head(santon)
        date_time rh wd  ws                date gr10 no no2 nox pm10 so2
1 01/01/2005 00:00 31 207 2.4 2005-01-01 00:00:00 NA NA NA NA NA NA
2 01/01/2005 01:00 31 215 2.4 2005-01-01 01:00:00 NA NA NA NA NA NA
3 01/01/2005 02:00 30 212 2.3 2005-01-01 02:00:00 NA NA NA NA NA NA
4 01/01/2005 03:00 30 190 2.2 2005-01-01 03:00:00 NA NA NA NA NA NA
5 01/01/2005 04:00 30 188 1.8 2005-01-01 04:00:00 NA NA NA NA NA NA
6 01/01/2005 05:00 30 192 2.1 2005-01-01 05:00:00 NA NA NA NA NA NA
```

which shows the field names and values of the first 6 lines.

Two met data sets from the North Lincolnshire network are available for use in this case study – Scunthorpe Town and Killingholme.

3.3 Initial met data processing

Before detailed analysis can begin it is essential to correctly format and quality check the data that is being interrogated. In the case of the pollution data from the North Lincolnshire monitoring network, this is quality assured and controlled under AEA's 'Cal Club' to the same standard as data from the UK National network (AURN) and is therefore of a high standard. Other than correctly formatting, no pre-processing was needed to prepare this data.

The met data however, are essential for some of the more powerful directional analysis that can be performed and these data are not included in any formal quality control procedures. It is therefore time well spent checking it at the start to make sure that any obviously erroneous data are omitted.

In the absence of formal QA procedures for the met data, some care and consideration was taken at the outset to ensure that the met data was of sound quality. This consisted of obtaining summary statistics for the two possible met data sets to examine the range of wind speeds and wind directions as per the code below. A useful function to see the distribution of these values quickly is to create a histogram which will rapidly illustrate any obvious errors. In this case the operations that were used simply set any negative data to NA and set any excessively high wind speeds to NA. The most important aspect concerning the use of meteorological data is the representativeness of the site. If a site is, for example, influenced by a nearby building or other structures, the data may be unusable, even though the measurements are accurately made. On this basis, data from the Scunthorpe Town site were chosen, based on the open-nature of the surrounding area.

```
# 4) check met
summary(met_kill)
summary(met_scun)

#min ws at Scun contains negatives:
min(met_scun$ws, na.rm = TRUE)

#therefore change negatives to NA:
met_scun$ws[met_scun$ws < 0] <- NA

#max ws at Scun is also a little high:
max(met_scun$ws, na.rm = TRUE)
hist(met_scun$ws)

#therefore find ids where ws over 20ms/sec and set to NA:
ids <- which(met_scun$ws > 20) #find location of ws > 20
met_scun$ws[ids] <- NA #sets to NA
rm(ids) #$
```

In order to perform directional analysis on daily Partisol PM_{10} data some additional processing was required to determine daily average wind speed and wind direction. Averaging wind speed is a simple task but the concept of an average wind direction requires more effort. As a result, some additional functionality was added to **openair** based on the code below . Note that a separate function to simplify and automate this common task can be found in Carslaw and Ropkins (2009).

```
#average standard met variables
#wind speed
ws <- tapply(met_scun$ws, list(format(met_scun$date,"%Y-%m-%d")), mean, na.rm = TRUE)
ws <- as.vector(ws)
```

```
rh <- tapply(met_scun$rh, list(format(met_scun$date,"%Y-%m-%d")), mean, na.rm = TRUE)
rh <- as.vector(rh)

#dates expressed as days
dates <- as.Date(seq(met_scun$date[1], met_scun$date[nrow(met_scun)],
        length = length(ws)))

#for wind direction, calculate the components
u <- sin(2 * pi * met_scun$wd / 360)
v <- cos(2 * pi * met_scun$wd / 360)

#daily means of the components
mean.u <- tapply(u, list(format(met_scun$date,"%Y-%m-%d")), mean, na.rm = TRUE)
mean.v <- tapply(v, list(format(met_scun$date,"%Y-%m-%d")), mean, na.rm = TRUE)

#mean wd (theta)
theta <- as.vector(atan2(mean.u, mean.v) * 360 /2 / pi)

#correct for negative wind directions
theta[theta < 0 & !is.na(theta)] <- theta[theta < 0 & !is.na(theta)] + 360

#make a new daily met file...
dailymet_scun <- data.frame(date = dates, ws = ws, wd = theta, rh = rh)
```

This produced a daily met data file for Scunthorpe Town that was then merged with the Partisol PM_{10} data sets in the same way as the standard hourly met data was merged with the other pollutant data sets. It was then possible to produce polar plots in a similar way to that for hourly data.

3.4 Exploratory data analysis

An important step in analysing data is to consider *exploratory data analysis*. Often, by looking at various data summaries, problem data or interesting features can be found. In the former case it would then perhaps be necessary to consider removing such data. Analysing lots of data in this way can be time consuming, and hence it is a step that is often not undertaken.

In **openair** there is a dedicated function to help explore data before further analysis is undertaken. The function is called **summarise** and it is called very simply, e.g.:

```
summarise(santon)
```

Figure 2 conveniently shows all the data in one plot. For each numerical variable in a data frame (in this case Santon), a plot is made, shown in the left panel, showing where data exist (blue) and missing data (red). For clarity, only running sequences of $\geq$ 24 hours of missing data are shown. It is easy to see therefore missing data at the end of 2006 and into 2007 for NO, NO_X, NO_2 and SO_2. Also shown in each panel are statistical summaries, which include: number of missing points (with percentage shown in parentheses), minimum, maximum, mean, median and the 95th percentile. For each year, the data capture (%) is shown in green font. So, for example, the data capture for NO_X in 2007 was 51.7 %.

The plots shown in the right panel are *density plots* showing the distribution of the data. Here it is shown that SO_2 concentrations are generally below 20 μg m^{-3}. With these plots it is also easy to see that the prevailing wind direction is westerly at this location.

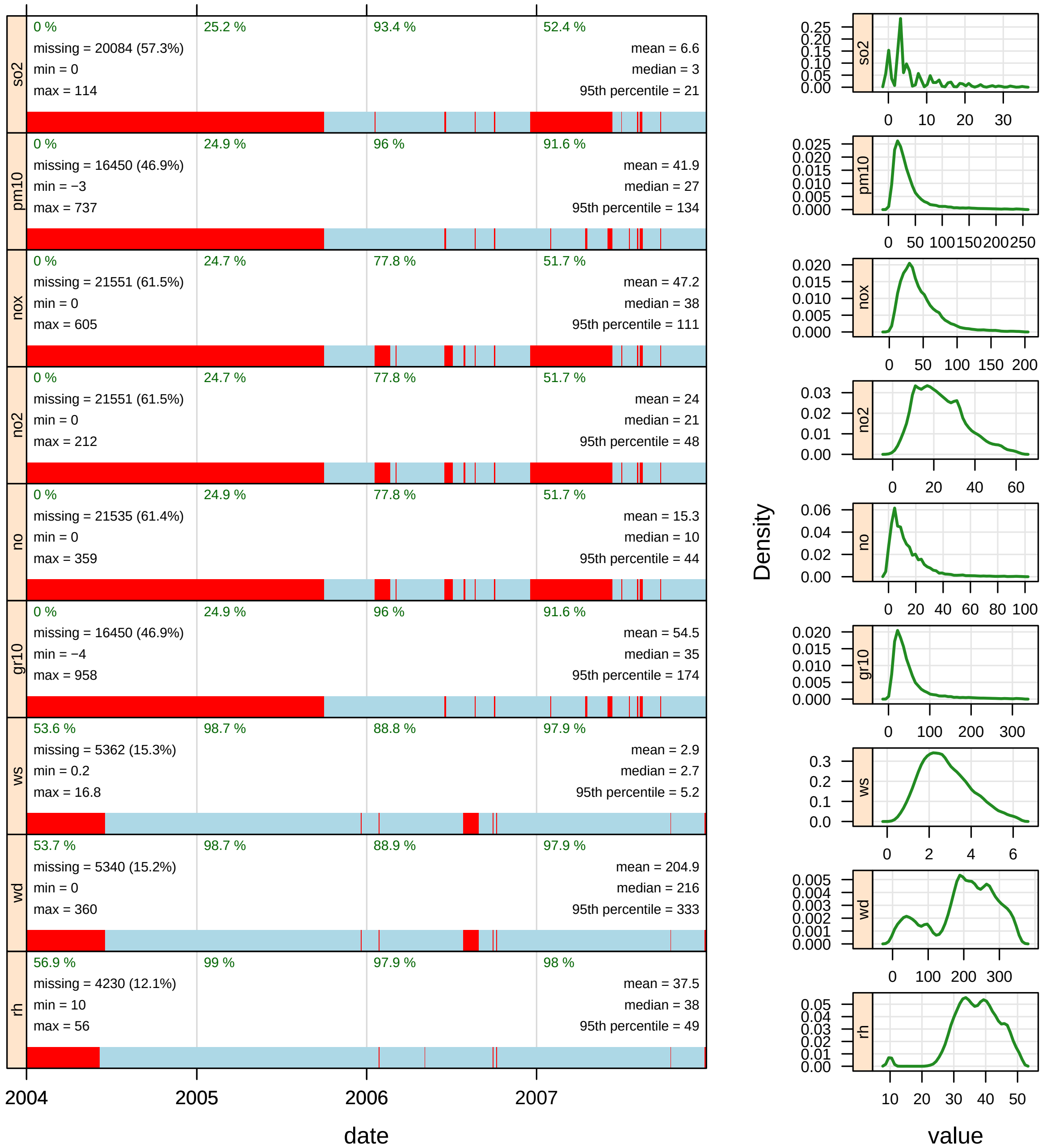

Figure 2: Exploring the data at Santon using the `summarise` function. The plots in the left panel show data (light blue), missing data (red) and other summary statistics. For each year the data capture is shown as a percentage. The panels on the right show the distribution of the data using a *density plot*.

4 Analysis of meteorological data

4.1 Data from Scunthorpe

There were two potential meteorological sites available to use in the analysis: in Scunthorpe and Killingholme. Because most of the analysis conducted in this report depends on the use of appropriate meteorological data, it is important to establish which data set is most suitable. Ideally the measurements should be made close to sources and receptors of interest and the measurements should not be too strongly affected by local features such as buildings. The first part of the analysis uses the **wind.rose** function to provide a quick overview of the data. This is applied to both data sets. Note that the wind speed interval **ws.int** is set to 1. The plots are shown in Figure 3 and 4, respectively.

```
#for Scunthorpe
wind.rose(met_scun, ws.int = 1, main = "Wind roses by year for the Scunthorpe site")

#for Killingholme
wind.rose(met_kill, ws.int = 1, main = "Wind roses by year for the Killingholme site")
```

The are several points that can be noted from Figure 3 and 4. First, data at the Killingholme site cover a greater number of years (2003 – 2007). Second, wind speeds at the Scunthorpe site are higher. Finally, there are potentially important differences in the frequencies of wind speeds/directions between the two sites. For example, in 2006, only 10 % of the winds were from the south at Killingholme, where as southerly winds accounted for 20 % of the winds at Scunthorpe. It is important to stress that these plots do not account for data capture, which if significantly different between the sites could account for some of the differences. Based on a consideration of the location of the instruments it was decided to base the analysis on data from the Scunthorpe site – even though the data covered fewer years compared with Killingholme. The principal reason for this decision was that the Scunthorpe site is located in a more open environment.

An alternative way to plot these data is to use the **polar.freq** function, which bins the data by wind speed and direction and shows the frequency as different colours. The plot (shown in Figure 5) highlights some anomalously high wind speeds in 2006 and 2007, which would be worth checking.

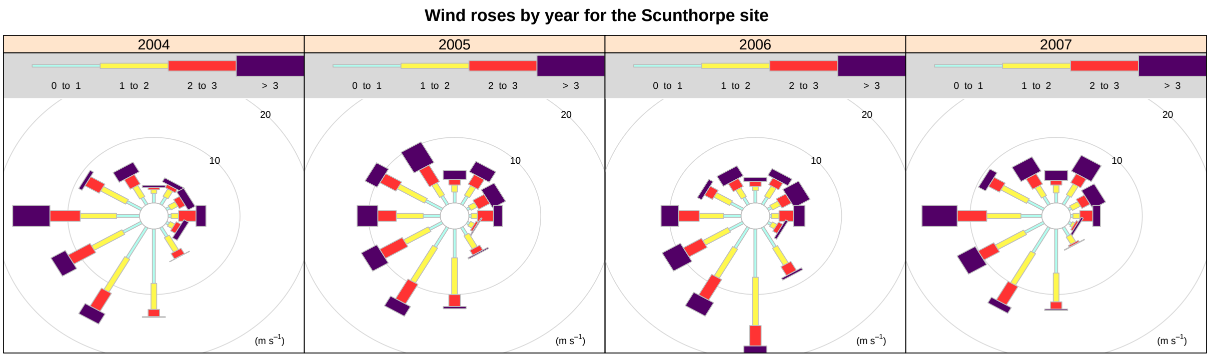

Figure 3: Wind roses by year at the Scunthorpe site.

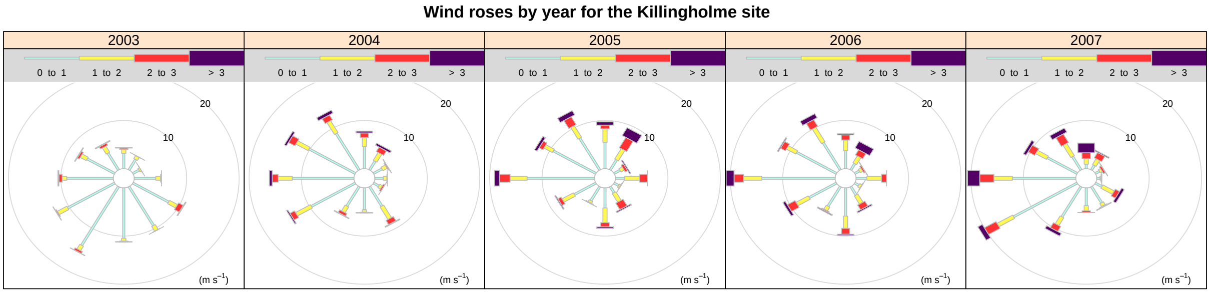

Figure 4: Wind roses by year at the Killingholme site.

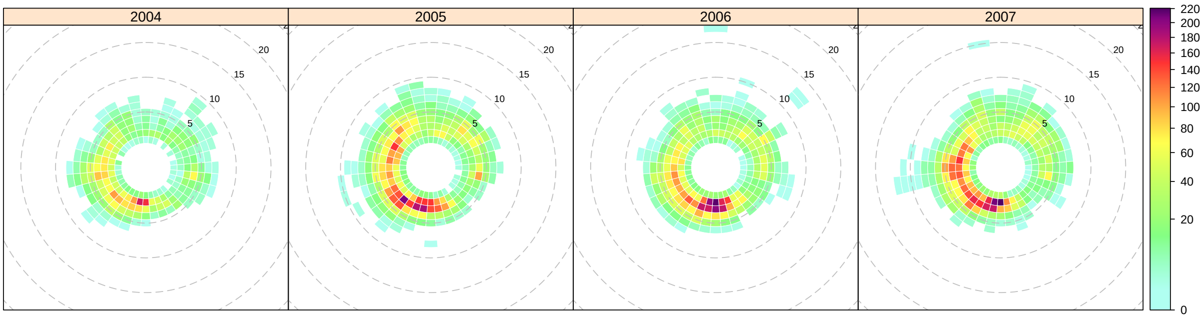

Figure 5: Alternative wind rose type plot for Scunthorpe using the `polar.freq` function. The colour scales gives the frequency of occasions where the wind speed was from a certain wind direction and for different wind speed ranges.

4.2 Data from Church Fenton

Given the importance of meteorological data consideration was also given to the Met Office site at Church Fenton (approximately 40 km from Scunthorpe). These data are presented only for comparison as part of ongoing research. Probably the most important aspect of the data are the wind directions because these are used to draw influences about potential sources. In this respect, the Church Fenton site and the Scunthorpe Town site do show similar wind direction frequencies e.g. higher frequencies of westerly winds in 2004/2007 and southerly winds in 2006. The Church Fenton data do have higher mean wind speeds (4.3 versus 2.9 m s^{-1}); most likely due to the higher met mast height at Church Fenton.

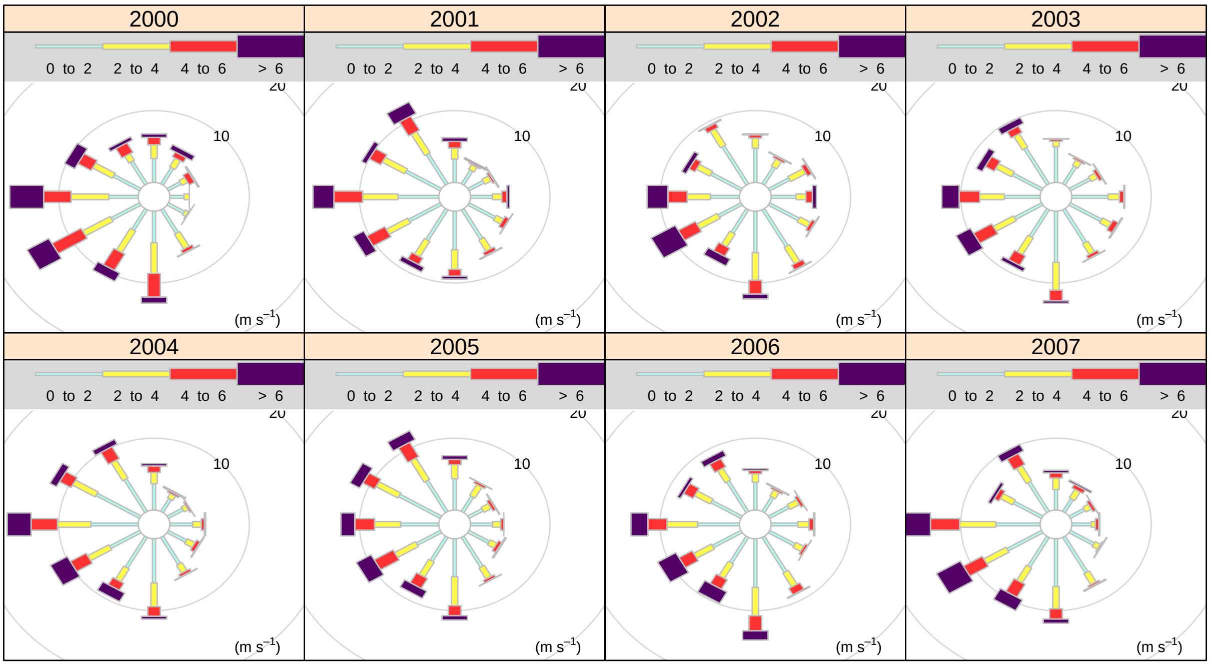

Figure 6: Wind roses by year for the Met Office Church Fenton site.

5 Investigating sources using polar plots

5.1 Polar plots for SO_2

We first focus on investigating sources of SO_2 using the `polar.plot` function for three sites: Scunthorpe Town, Santon and Killingholme. These plots are straightforward to produce singularly e.g. for Scunthorpe Town:

```
polar.plot(scunthorpet, pollutant = "so2", cols = "jet", title = "Scunthorpe Town")
```

However, the code below shows how to plot three in a row. In addition, to capture more detail in the plots, auto-smoothing is set to FALSE and the smoothing parameter set to 100 – see Carslaw and Ropkins (2009) for more details.

```
plt1 <- polar.plot(killingholme, pollutant = "so2", cols = "jet",
        main = "Killingholme", auto.smooth = FALSE, k = 100)
plt2 <- polar.plot(santon, pollutant = "so2", cols = "jet",
        main = "Santon", auto.smooth = FALSE, k = 100)
plt3 <- polar.plot(scunthorpet, pollutant = "so2", cols = "jet",
        main = "Scunthorpe Town", auto.smooth = FALSE, k = 100)

#shows how to plot 3 in a row
print(plt1, split = c(1, 1, 3, 1), more = TRUE)
print(plt2, split = c(2, 1, 3, 1), more = TRUE)
print(plt3, split = c(3, 1, 3, 1))
```

The plots shown in Figure 7 clearly indicate sources of SO_2 at all three sites, but with different dominant wind directions. At Scunthorpe Town, the high concentrations are observed and these arise from sources to the south-east. However, the is perhaps evidence of another source(s) to the east. At Santon, the highest concentrations are from the west, where again there is some indication of two groups of sources. At Killingholme there is evidence of several SO_2 source to the NE.

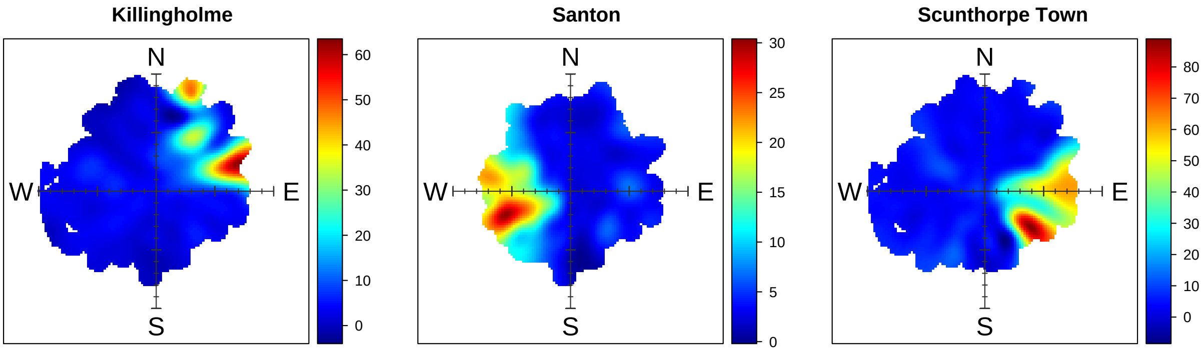

Figure 7: Bivariate polar plots for SO_2 at three different sites, clearly showing sources of SO_2 at all sites. The colours show the concentration of SO_2 in $\mu g\ m^{-3}$.

5.2 NO_X at Gallagher retail park and Kingsway House

One important issue to consider is whether the features seen on polar plots are likely to be "real" sources. In some cases it is possible that erroneous data could produce patterns similar to that for real sources. Another potential concern is that certain features may only consist of one point. A way of testing this is to set a lower limit for the number of readings required in each wind speed/direction "bin", before the smoothing is done. This is illustrated with NO_X concentrations at Gallagher retail park and Kingsway House, which both show potentially interesting features to the north.

The polar plots for these sites are shown in Figure 8. As shown at Gallagher retail park (top left), there is some evidence of increasing concentrations at high wind speeds from the NNE. However, if "bins" are only used that have more than one point (top right), this feature disappears. One can conclude therefore that only one point contributes to this feature and conclusions about whether the source is real or not would need to be considered carefully. [1]

By contrast, the data at Kingsway House are different. Again, there is some evidence of a source to the north (bottom-left). In this case though, when using only bins with two or more points, the feature remains, perhaps providing more evidence of a real source. For both Gallagher retail park and Kingsway House it is important to consider other issues such as data capture, and to follow the analysis up in alternative ways.

The code that produced Figure 8 is shown below.

```
plt1 <- polar.plot(gallagher, poll = "nox", col = "jet",
       main = expression("Gallagher retail park NO" [X] * ""))

plt2 <- polar.plot(gallagher, poll = "nox", col = "jet", min.bin = 2,
       main = expression("Gallagher retail park NO" [X] * " (min.bin = 2)"))

plt3 <- polar.plot(kingsway, poll = "nox", col = "jet",
       main = expression("Kingsway House NO" [X] * ""))

plt4 <- polar.plot(kingsway, poll = "nox", col = "jet", min.bin = 2,
       main = expression("Kingsway House NO" [X] * " (min.bin = 2)"))

print(plt1, split = c(1, 1, 2, 2), more = TRUE)
print(plt2, split = c(2, 1, 2, 2), more = TRUE)
print(plt3, split = c(1, 2, 2, 2), more = TRUE)
```

[1] Note that at high wind speeds there tend to be fewer points anyway, so care is needed when drawing conclusions from these plots.

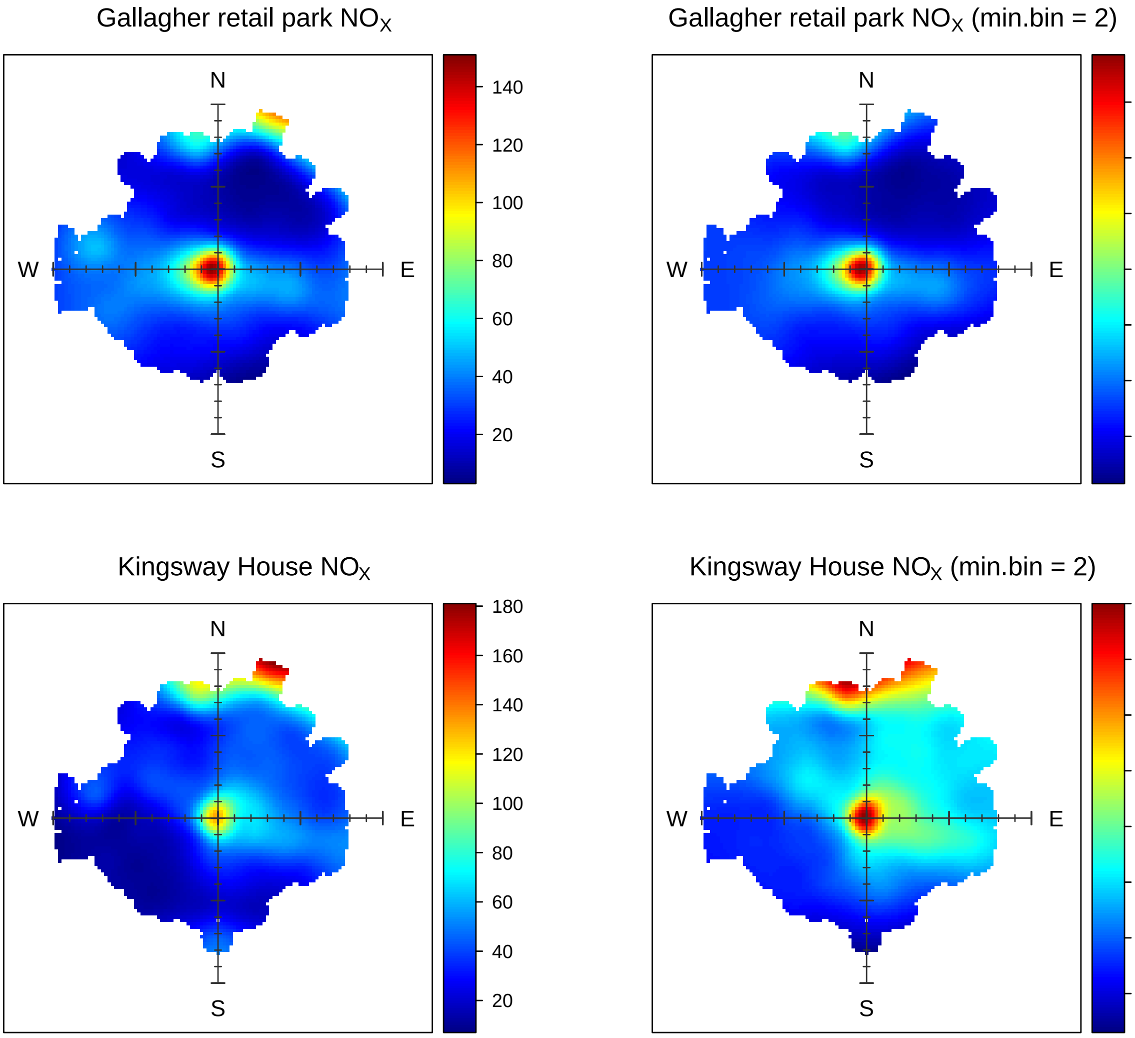

Figure 8: Bivariate polar plots for NO_X at Gallagher Retail Park and Kingsway House, showing the effect of setting a minimum **`min.bin`** size. The colours show the concentration of NO_X in μg m^{-3}.

```
print(plt4, split = c(2, 2, 2, 2))
```

5.3 Are there two sources of SO_2 and PM_{10} that can be identified at Santon?

The previous section showed that at Santon there was evidence of an important source of SO_2 and PM_{10} (and to some extend NO_X) from the direction of the steel works. It is useful to consider whether more information can be gained by analysing the data in a different way.

One useful way to analyse concentrations is to plot the percentiles. Better still, is to further show how percentile concentrations vary by wind direction and wind speed – both of which can aid source identification. In the **`openair`** package, the **`polar.percentile`** function has this capability.

```
polar.percentile(santon, pollutant = "so2")
```

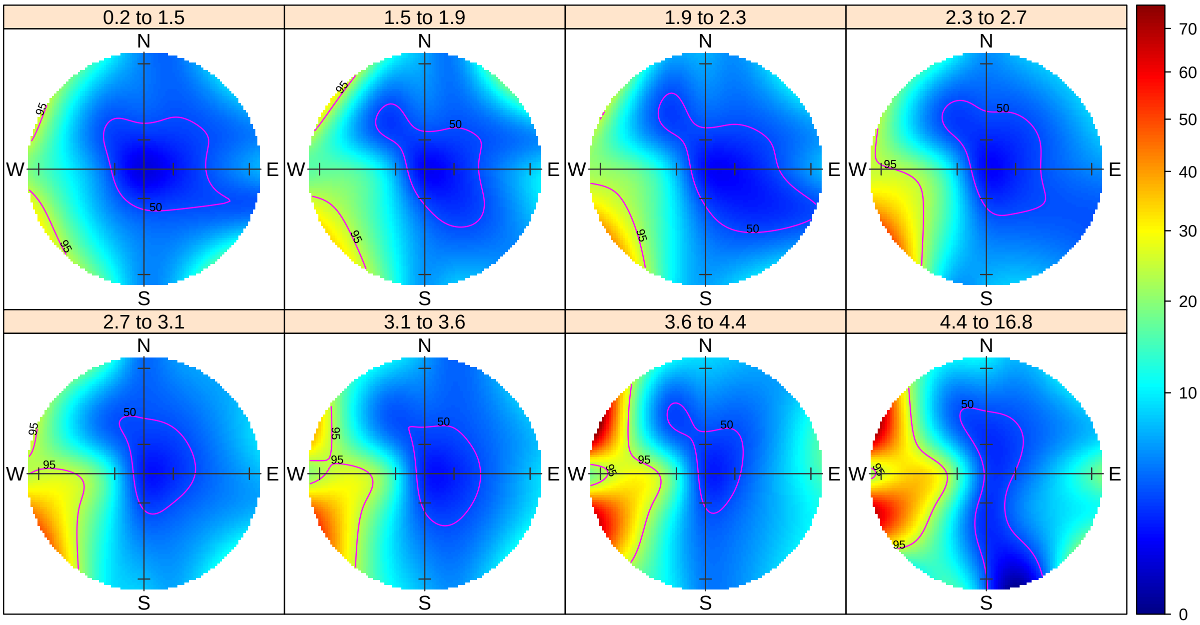

Figure 9: The **polar.percentile** function applied to SO_2 concentrations at Santon. Each panel shows the wind speed range (the first being 0.2 to 1.5 m s^{-1}). Percentile concentrations are shown by colour with the zero percentile shown in the centre of each plot and the 100th i.e. peak concentration, shown at the circumference. The magenta lines shown on each plot highlight the respective 50th and 95th percentile concentrations.

Figure 9 shows how the percentile concentrations of SO_2 vary by wind speed range (lowest 0.2–1.5 m s^{-1} to 4.4–16.8 m s^{-1}, highest). The clearest variation shown in this plot as the wind speed range increases is the increase in the concentration of SO_2; consistent with pervious analysis. However, there seem to be two effects. At moderate wind speeds (1.9 to 3.6 m s^{-1}) a source to the WSW emerges. For higher wind speeds (3.6 to 16.8 m s^{-1}) a source to the WNW becomes more important. This *might* indicate that two separate high-level sources of SO_2 affect Santon. A possible explanation of this sort of behaviour is that there are two source types maybe with different stack heights (and therefore different dispersion characteristics). A very similar plot (not shown) was also derived for PM_{10}.

5.4 Using the polar.annulus function

The **polar.annulus** is an extension of the **polar.plot** function that allows data to be plotted by different temporal periods (hour of day, month of year, day of week and trend). By plotting the data as an annulus, there is less compression at the centre, which can help provide a better visual impression of how concentrations vary. The basic plot can be called by:

```
polar.annulus(santon, pollutant = "pm10", type = "hour")
```

For more information on the use of this function, see Carslaw and Ropkins (2009). To show its use applied to North Lincs data, we have applied it to the Santon site for PM_{10} and SO_2 concentrations, by hour of day and month of year. Figure 10 show the four plots together. Taking the SO_2 plot by hour of the day as an example (top left in Figure 10), the following should be noted. Concentrations are plotted by wind direction in the usual way.

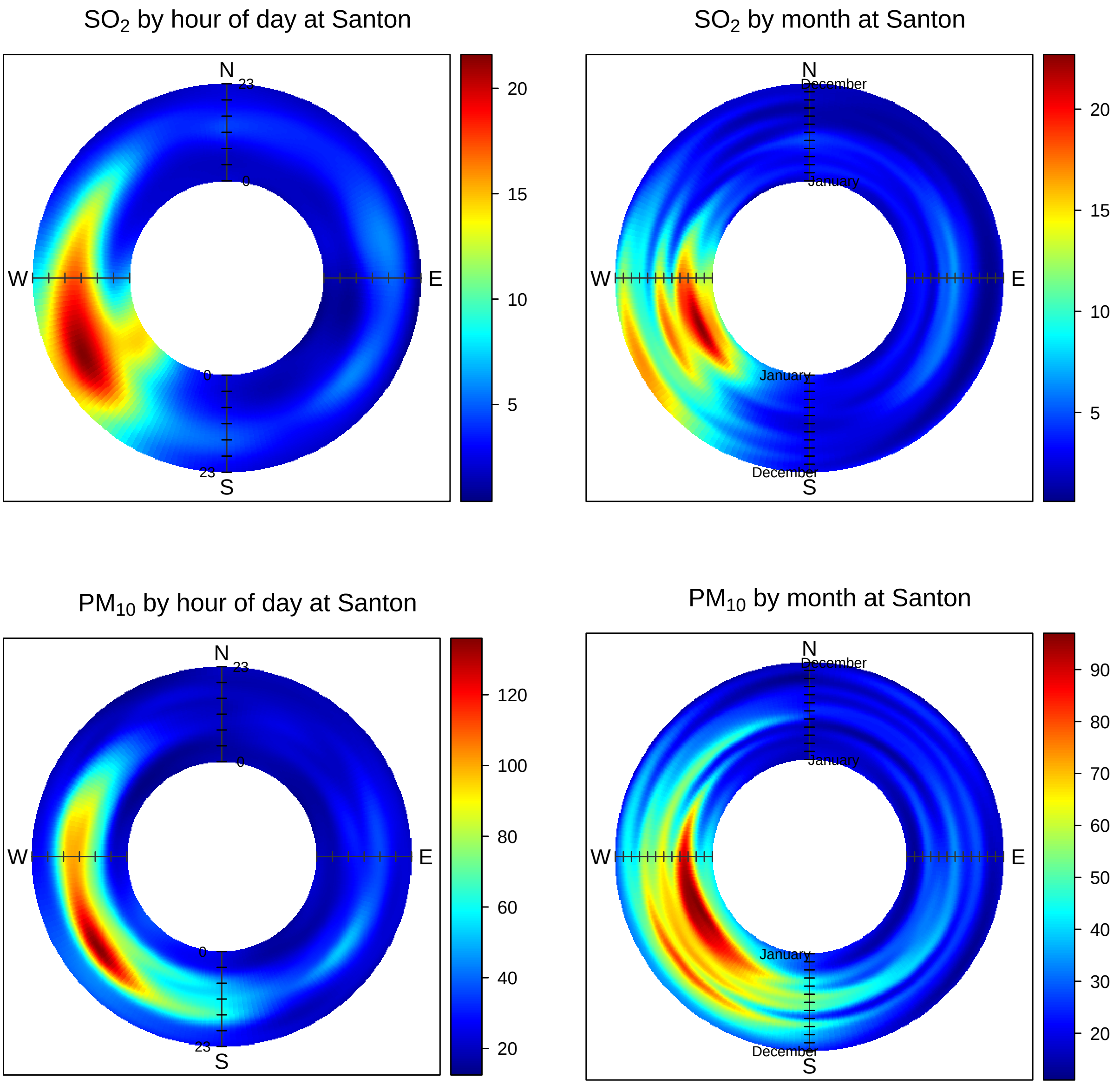

Figure 10: Polar annulus plots for SO_2 and PM_{10} at Santon, by hour of day and month of year. The plots show how concentrations vary by time (e.g. hour of day, month of year) with the earliest time shown in the inner circle and the latest time at the outer circle. All units are in µg m^{-3}. Taking the PM_{10} concentrations at Santon as an example, the highest concentrations were observed for south westerly winds during the spring/early summer.

Second, the inner part of the annulus represents hour = 0 and the outer part hour =23. Therefore, moving across the annulus moves through the hour of the day. In this respect, the highest concentrations of SO_2 at Santon are seen for wind directions from 220 - 280° and from around 8 am to 11 pm.

It is apparent that the plot for PM_{10} concentrations is similar to SO_2– but with a more obvious, higher concentration peak in the middle of the day. The seasonal plots do not highlight anything particularly interesting, and it would be worth replotting these when more data are available.

For information, the code that makes Figure 10 is:

```
plt1 <- polar.annulus(santon, poll = "so2", cols = "jet",type="hour",
        main = expression("SO" [2] * " by hour of day at Santon"))

plt2 <- polar.annulus(santon, poll = "so2", cols = "jet",type="season",
       main = expression("SO" [2] * " by month at Santon"))

plt3 <- polar.annulus(santon, poll = "pm10", cols = "jet",type="hour",
       main = expression("PM" [10] * " by hour of day at Santon"))

plt4 <- polar.annulus(santon, poll = "pm10", cols = "jet",type="season",
       main = expression("PM" [10] * " by month at Santon"))

print(plt1, split = c(1, 1, 2, 2), more = T)
print(plt2, split = c(2, 1, 2, 2), more = T)
print(plt3, split = c(1, 2, 2, 2), more = T)
print(plt4, split = c(2, 2, 2, 2))
```

6 Investigating the temporal nature of emissions

6.1 Filtering by wind speed and direction

This section provides some examples of how source characteristics can be analysed in more depth by considering their temporal variation.

We first consider how concentrations of SO_2 vary by hour of the day and day of the week at Santon using the **diurnal.error** function. The results are shown in Figure 11. This function is very useful for assessing different source influences, particularly when used with data filtering (e.g. by wind speed and direction). By default, the plots are shown in *local time*, which helps to give a clearer indication of variation by hour of day. [2]

```
diurnal.error(santon, pollutant = "so2", ylab = expression("SO" [2]))
```

Note that a slightly more refined way to do this analysis would be to limit the wind directions (and possibly wind speeds) based on the polar plots. Figure 7 shows that the source of interest is most apparent when the wind is westerly. Therefore, to filter for those conditions, one can use the **subset** command:

```
diurnal.error(subset(santon, wd > 180 & wd < 360), pollutant = "so2",
   ylab = expression("SO" [2]))
```

This filtering should give a slightly better indication of the effect of the sources(s) identified in the polar plot. Figure 12 shows for example that concentrations tend to peak at 3 pm each day and are lowest on Sundays. Also, concentrations tend to increase throughout the week and peak on Fridays. Such information could usefully be compared with any source information at this location.

Further filtering (limiting also to wind speeds > 4 m s^{-1}) indicates that there is less evidence for a day of week effect, although the uncertainties are greater because of the lack of data that meets these conditions. With more data – even one year more, a better assessment could be made of the specific source features of interest. However, the principles of investigating sources by these methods hold.

[2] Most emissions vary by local time e.g. rush hour occurs at 8 am local time. During British Summer Time (BST), the emissions are effectively released at GMT – 1. The **diurnal.error** function automatically corrects time to local time to ensure a better matching between BST and GMT. It can also work with just GMT.

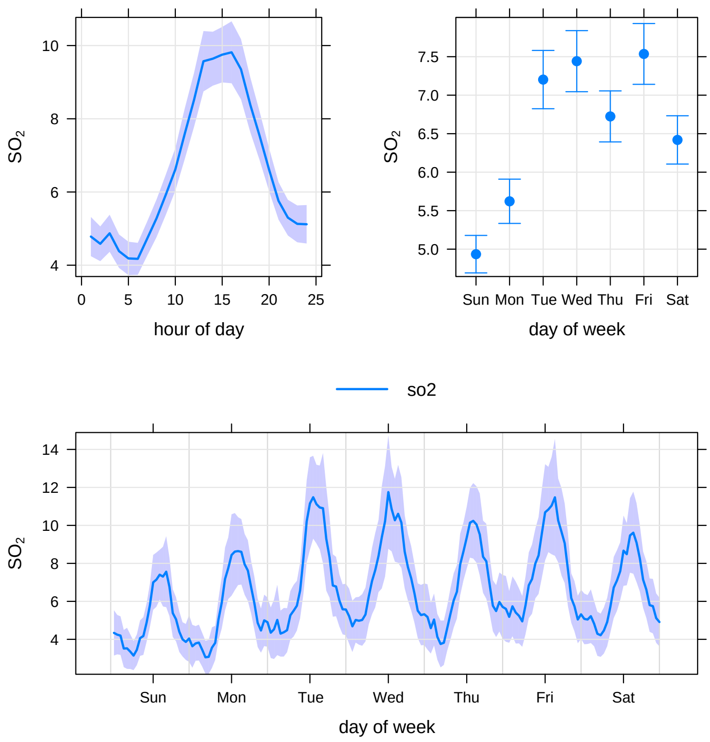

Figure 11: Investigating how concentrations of SO_2 (in µg m^{-3}) vary at the Santon site using the **diurnal.error** function. The plot shows how concentrations vary by time of day and day of week. The shading shows the 95 % confidence intervals in the mean concentration.

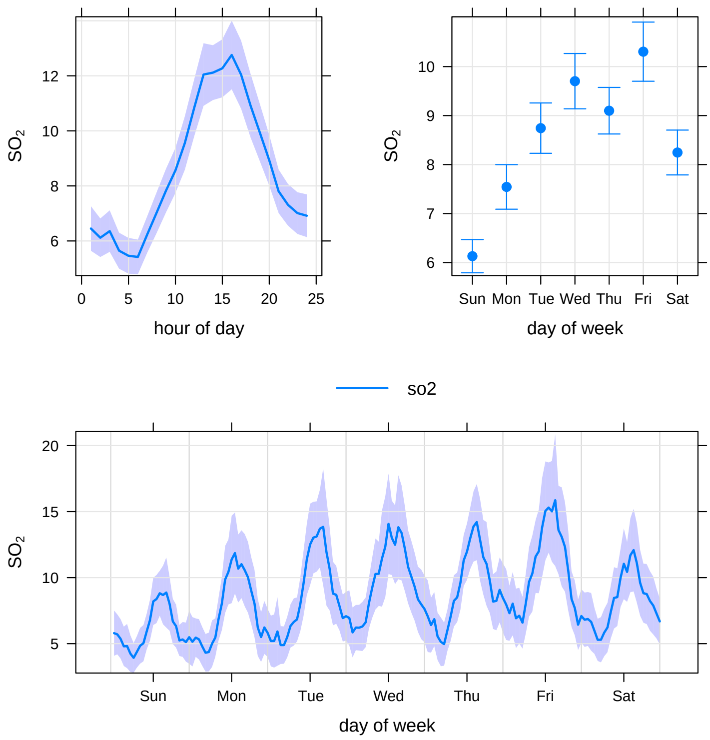

Figure 12: Investigating how concentrations of SO_2 (µg m^{-3}) vary at the Santon site with wind directions filtered to focus on the source(s) of interest.

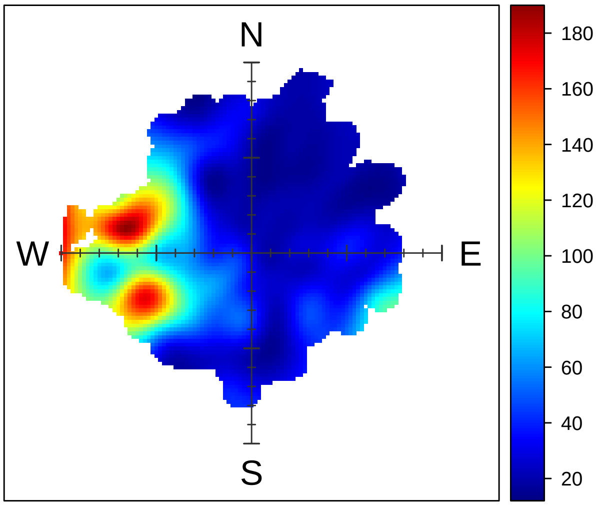

Figure 13: Bivariate polar plot for PM_{10} at Santon. THe colour scale shows the concentration in µg m^{-3}.

Given that the temporal variation in SO_2 is very clear, it is useful to consider whether any other pollutants also vary in this way. Because SO_2 is a combustion source, it would be interesting to know whether concentrations of PM_{10} vary in a similar way. If they do, this would provide a strong indication that the source of PM_{10} is also likely to be similar i.e. combustion dominated. This is an important characteristic to confirm, because it could mean for example that PM_{10} concentrations are not dominated by wind-blown resuspension from spoil heaps but are maybe more controllable combustion sources. However, first it is useful to check the polar plot for PM_{10} at Santon:

```
polar.plot(santon, pollutant = "pm10", cols = "jet",
           title = "Santon", auto.smooth = FALSE, k = 100)
```

Figure 13 shows many similar characteristics to the SO_2 plot for Santon shown in Figure 7, which provides the first strong evidence that the sources are similar. More evidence is gained by considering the temporal characteristics:

```
diurnal.error(subset(santon, wd > 180 & wd < 360), pollutant = "pm10",
    ylab = expression("PM" [10] ))
```

The temporal characteristics are shown in Figure 14. There are clearly some strong similarities between this plot for PM_{10} and Figure 12 for SO_2. In particular, concentrations tend to peak at around 3 pm each day, and concentrations also tend to increase throughout the week and peak on Friday. Taken together, this analysis shows that for westerly winds at Santon concentrations of SO_2 and PM_{10} are likely dominated by the same (combustion) source. This is potentially very useful information concerning mitigation i.e. controlling combustion sources of SO_2 *and* PM_{10} could be very effective at this location. However, to be sure that this is indeed the case, $PM_{2.5}$ measurements would be extremely helpful.

Perhaps a better approach for comparing PM_{10} and SO_2 at Santon would be to plot them together on the same plot. Unfortunately, the problem is that they each have very different scales. One approach is to "normalise" the concentrations by dividing them by their mean values. In addition, better-defined diurnal profiles are more likely if some attempt is made to first subtract background concentrations. Considering wind directions and availability of data, it would make sense to subtract Scunthorpe Town concentrations for westerly winds. However, some processing is required first. What is needed is a file (data frame in R) that

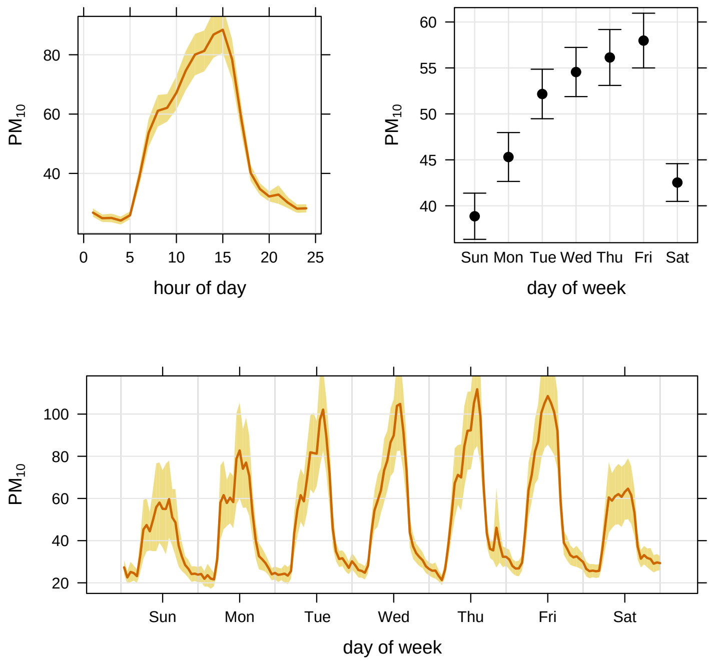

Figure 14: Investigating how concentrations of PM_{10} (in µg m^{-3}) vary at the Santon site with wind directions filtered to focus on the source(s) of interest.

contains the difference in concentrations of PM_{10} and SO_2 between Santon and Scunthorpe Town. This has been done in chunks below.

```
#select columns of interest from Santon
sant <- subset(santon, select = c("date", "so2", "pm10"))
#rename columns
names(sant)[2:3] <- c("sant.so2", "sant.pm10")

#select columns of interest from Scunthorpe Town
scun <- subset(scunthorpet, select = c("date", "so2", "pm10", "ws", "wd"))
#rename columns
names(scun)[2:3] <- c("scun.so2", "scun.pm10")

#merge santon and scunthopre (this will match dates)
mydata <- merge(sant, scun)

#calculate new columns for differences in PM10 and SO2
mydata$pm10 <- mydata$sant.pm10 - mydata$scun.pm10
mydata$so2 <- mydata$sant.so2 - mydata$scun.so2

#plot the diurnal error
diurnal.error(subset(mydata, wd > 180), poll=c("so2", "pm10"), normalise = TRUE,
     name.pol = c(expression("SO" [2]), expression("PM" [10])))
```

Figure 15 shows how the normalised concentrations of PM_{10} and SO_2 compare. It is clear from this plot that the behaviour of SO_2 and PM_{10} is very similar by hour of day and day of week. In particular, the way the concentrations increase to a maximum at around 4 pm (local time) does provide compelling evidence of similar source types. It should be noted that this analysis depends on the amount of data where there are both PM_{10} and SO_2 concentrations at *both* sites. The amount of data in this respect corresponds to about 12,000 hours (SO_2) and 18,000 hours (PM_{10}), respectively i.e. less than two years in each case. With more data it would perhaps be possible to gain a clearer idea of any differences. For

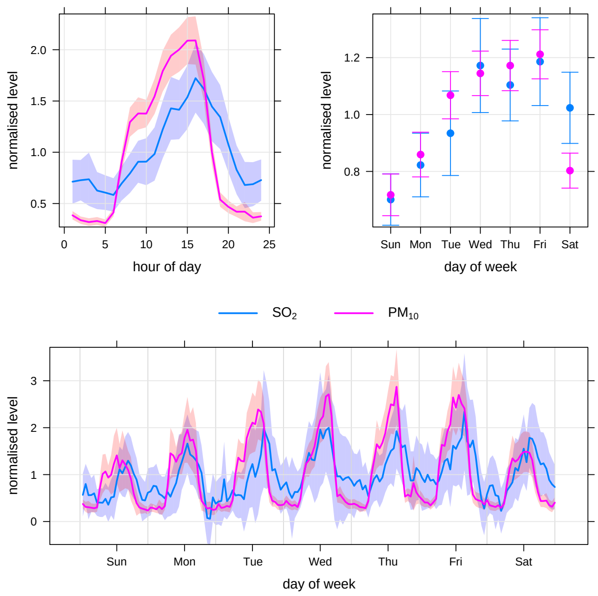

Figure 15: Diurnal variation in SO_2 and PM_{10} concentrations at Santon. Background concentrations from Scunthorpe Town have been subtracted. Note also that the concentrations have been normalised to make it easier to compare them.

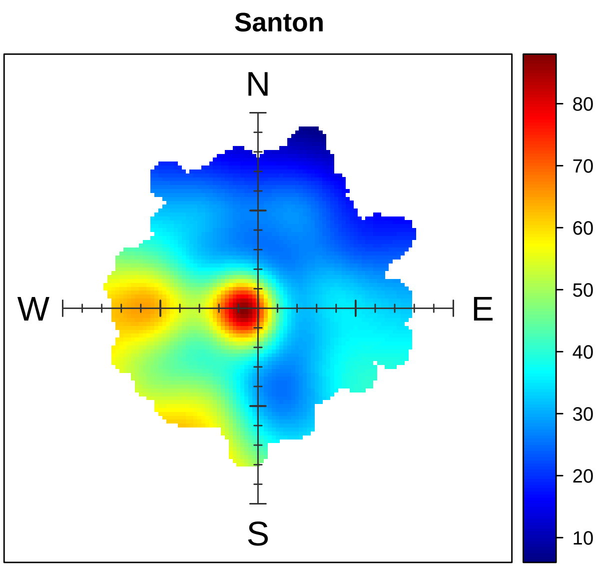

Figure 16: Bivariate polar plot for NO_X at Santon. The colour scale is in µg m^{-3}.

example, the two potential sources indicated by Figure 13 could be filtered further by wind speed and wind direction and then the `diurnal.error` function applied to each.

Following on from this analysis, consideration can also be given to NO_X. The polar plot suggests two potential source types. At low wind speeds from the west there are clearly high concentrations. However, at wind speeds > 3 m s^{-1} concentrations also appear to be high. This is an interesting example of the possible influence of two different source types. To investigate this potential, we separately plot the diurnal variations for westerly winds above and below 3 m s^{-1}.

It is difficult to completely separate two source influences, but it is apparent in this case that there are at least two important sources of NO_X. In Figure 17 where wind speeds >

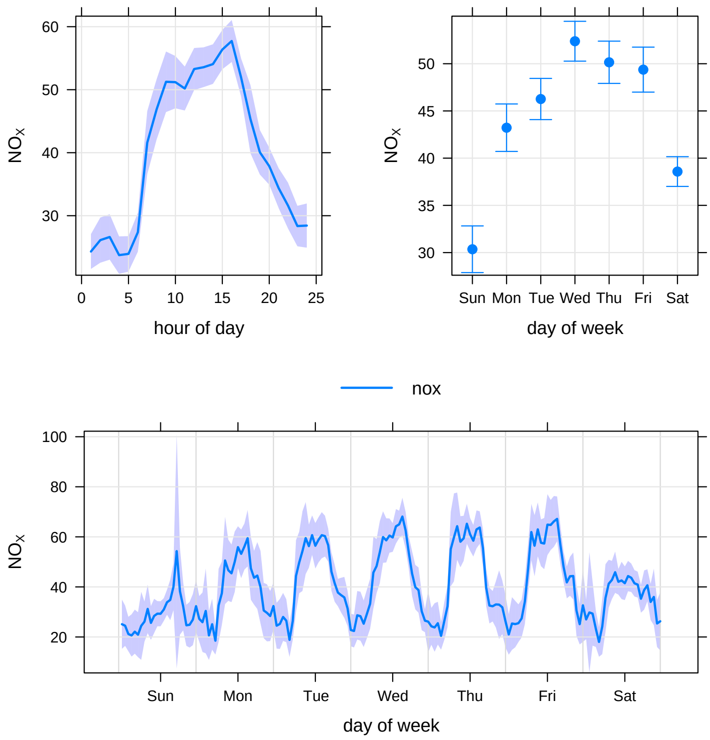

Figure 17: Investigating how concentrations of NO_X (μg m^{-3}) vary at the Santon site with wind directions filtered to focus on the source(s) of interest and wind speeds > 3 m s^{-1}.

3 m s^{-1} are considered, there are many similarities with the plots for PM_{10} and SO_2 e.g. concentrations peak around 3 pm and tend to increase throughout the week. By contrast, Figure 18 (wind speeds $\leq$ 3 m s^{-1}) has different characteristics: concentrations are lower at weekends and there is a double peak in NO_X throughout each day. The latter plot is typical of a road traffic source, while the former seems to be much more related to the same sources as SO_2 and PM_{10}.

```
#for ws > 3 m/s
diurnal.error(subset(santon, wd > 180 & wd < 360 & ws > 3), pollutant = "nox",
       ylab = expression("NO" [X]))

#for ws <= 3 m/s
diurnal.error(subset(santon, wd > 180 & wd < 360 & ws <= 3), pollutant = "nox",
       ylab = expression("NO" [X]))
```

6.2 Refining the polar plot

In the previous section it was shown that there were likely to be two sources of NO_X– or at least collections of different source types. In particular there was evidence of high concentrations of NO_X at low wind speeds for westerly winds. Concentration patterns of this type are typically seen at background sites strongly affected by ground-level sources; in this case most likely to be road traffic emissions. The question is, is it possible to gain a better indication of the industrial sources if background concentrations are first removed? This calculation can only be carried out when there are sufficient numbers of sites to use for the subtraction.

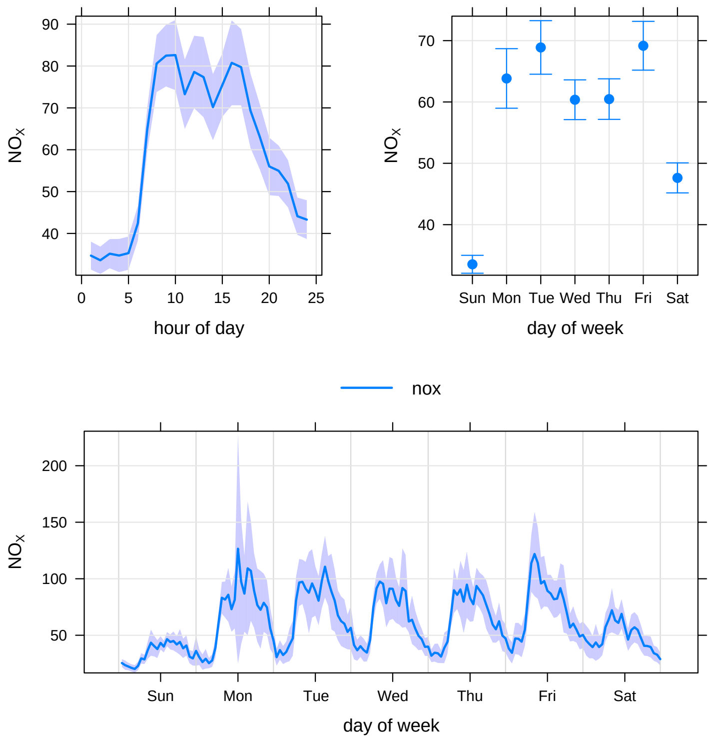

Figure 18: Investigating how concentrations of NO_X vary at the Santon site with wind directions filtered to focus on the source(s) of interest and wind speeds ≤ 3 m s^{-1}.

The choice of background site is perhaps never ideal. In this case the most appropriate site would be on the western boundary of the steel works, such that the subtraction would leave only the steel works contribution.

To make these calculations, some data preparation is required. [3] Unless the two data sets of interest start and end at exactly the same time, they will need matching by date/time. The aim is to make a new data frame that contains the pollutant of interest (NO_X at Santon) together with a background concentration of NO_X (which must be called something different). The code below does this in several steps, which could equally be applied to any combination of sites. First, only the date and concentration of NO_X is selected from the background site (Scunthorpe in this case). The name of the NO_X field is then changed to `background`. The two data frames are then merged and the difference between NO_X at Santon and the Scunthorpe background site calculated. Finally, a polar plot is produced.

```
#select only date and nox from a background site
temp <- subset(scunthorpet_noxco, select = c(date, nox))

#change the name to "background"
names(temp)[2] <- "background"

#merge the two data sets
santon <- merge(santon, temp)

#make a new field of the difference in nox, "diff"
santon$diff <- santon$nox - santon$background
```

[3] Note that code may be written to automate this subtraction.

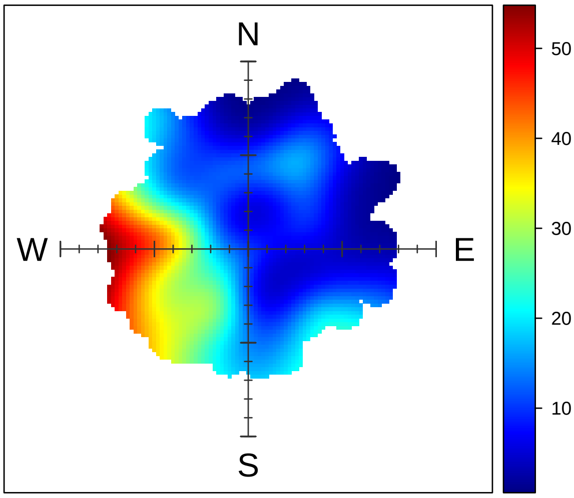

Figure 19: Bivariate polar plot for NO_X at Santon with background concentrations of NO_X removed using the Scunthorpe site. The colour scale is in µg m^{-3}.

```
#$run the polar.plot function
polar.plot(santon, pollutant = "diff", cols = "jet")
```

Figure 19 gives a much clearer indication of the industrial sources of NO_X; similar indeed to that for SO_2 and PM_{10} (compare with Figure 16, where the background has not been removed). However, there is less evidence in this case of two potential sources. There are several further useful calculations that could be made. Given a knowledge of source emissions in the site (i.e. emissions of NO_X, PM_{10} and SO_2), the ratios of different quantities could be calculated. Note that if this were done it would be important to ensure that all concentrations were in mass units (NO_X and SO_2 are in ppb). The polar plots could thus be used to isolate the conditions where the ratio calculations can be made – westerly winds, wind speeds > 3 m s^{-1} and with background removed. Such calculation would help confirm whether there is agreement with source inventories.

Note also that the calculations here could have been reversed. To gain a better idea of the possible industrial contribution to NO_X at the Scunthorpe NO_X site, the Santon NO_X concentrations could have been removed. Furthermore, for pollutants where the background concentration is high such as PM_{10}, background removal might actually be necessary to find evidence of a source. However, in this case it seems that the local source strength of PM_{10} is sufficiently hight that this is not necessary. Nevertheless, if making comparisons with source emission rates it would be advisable to remove background concentrations.

7 Trends

The first operation that most users will want to undertake when considering temporal trends is to have a look at the variation in concentrations of a pollutant its entire time range. This can be done in **openair** using the **trend.plot** function which calculates monthly means and fits a smooth line through them. This also provides a shaded area either side of the trend line, representing the 95 % confidence intervals in that trend. An example of this and the code used to generate it are shown below.

```
trend.plot(scunthorpet_noxco, pollutant = "no2",
          ylab = "concentration", deseason = TRUE, simulate = TRUE)
```

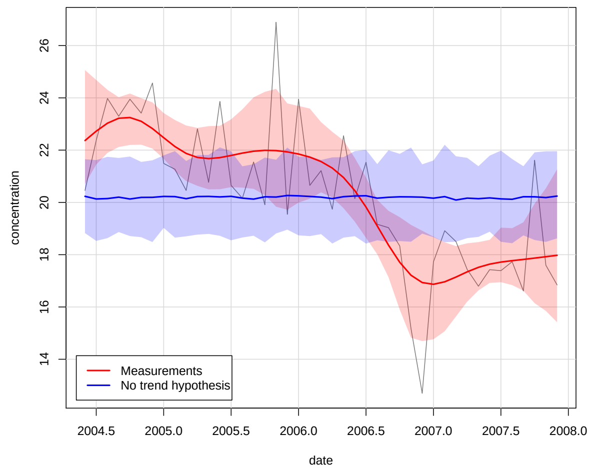

Figure 20: Trend in concentrations of NO_2 (µg m^{-3}) at Scunthorpe Town. Note the data have been deseasonalised.

This trend plot is from Scunthorpe Town NO_X and CO for NO_2 where there is enough data to make reasonable use of the function. This shows that from mid-2004 there was a gentle decline in NO_2 concentrations until late 2005 when this decline became more marked until 2007. From 2007 onwards concentrations became slightly elevated again. The general trend across the period is one of declining concentrations.

In order to see whether this decline is significant we can compare with the no trend hypothesis denoted in the code as 'simulate = TRUE'. The uncertainties of both lines are highlighted in the different colour shading. In the case above there is some overlap in the shaded areas, indicating that we cannot be confident that the decrease is significant. This is a simple way of quickly analysing the trend over time. As an example, using local knowledge in this case might linked this decline in NO_2 concentrations with a specific policy measure such as altered traffic flow patterns (associated with altered road layout) or the installation of improved abatement technology to an industrial source.

The corresponding trend plot for PM_{10} at Scunthorpe Town also shows interesting changes over time as shown below but the uncertainty of these trends (illustrated by the over lap of the shaded areas) suggests that these trends are less likely to be significant. Further development of the **openair** is likely to offer an alternative, more complex and quantitative method of assessing changes over time using a method known as 'Change Point Analysis.'

Data were also available for Scunthorpe Town PM_{10} and SO_2 before the site was moved. These trends are shown in Figure 22 and 23. While there is comparatively strong evidence of a downward trend in SO_2 concentrations, PM_{10} concentrations have tended to increase over the period.

These plots have been selected as interesting examples. There are other sites at which this style plots can be generated though the limited operational history of the North Lincolnshire network does not currently lend itself to useful and robust long-term trend analysis. As a result, other trend plots do not currently consist of sufficient data to apply these methods to. The principal value of this network is in its spatial coverage resulting from a large number of different sites rather than the length of time that they have been in operation. For this reason, we have concentrated the analysis more on short-term temporal variation such as diurnal profiles and analysis by day of the week. In future, as the operational record grows, analysis using wider range of temporal scales will become more robust.

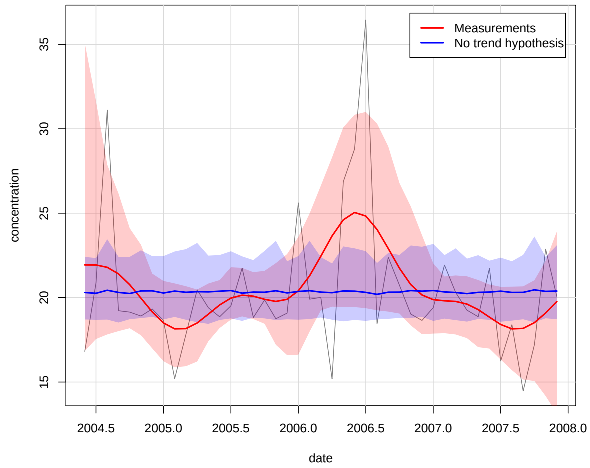

Figure 21: Trend in concentrations of PM_{10} ($\mu g\ m^{-3}$) at Scunthorpe Town. Note the data have been deseasonalised.

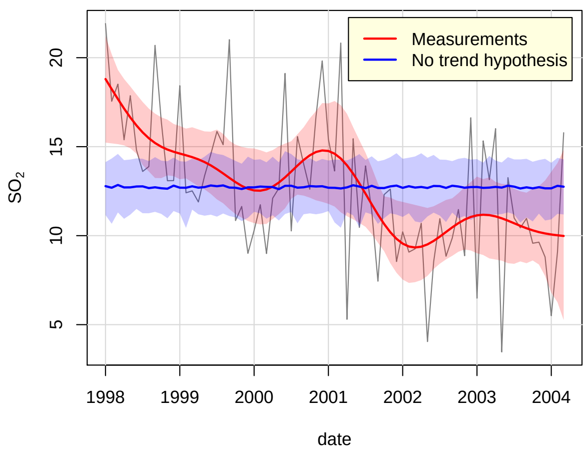

Figure 22: Trend in concentrations of SO_2 ($\mu g\ m^{-3}$) at Scunthorpe Town before the site was moved. Note the data have been deseasonalised.

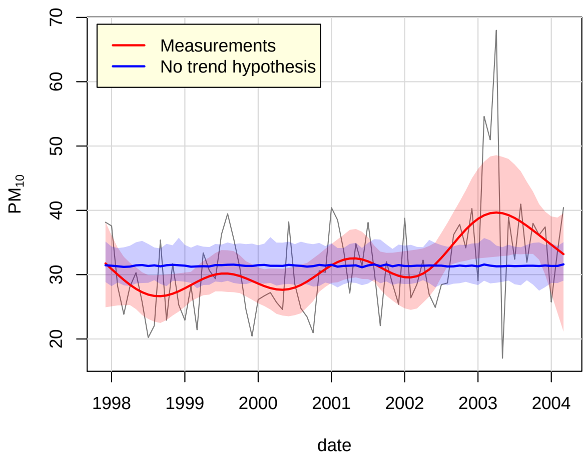

Figure 23: Trend in concentrations of PM_{10} ($\mu g\ m^{-3}$) at Scunthorpe Town before the site was moved. Note the data have been deseasonalised.

8 Spatial variations

Arranging the plots in this way allows the user an improved visualisation of the directional variation of different pollutants and, importantly, puts the directional analysis into spatial context of the different industrial sources over a wider area. In this way the triangulation of patterns shown in multiple polar plots in coordination can provide compelling evidence for specific sources, as shown in Figure 24.

In this case the polar plots have been created using their own optimal scale to best represent the sources. However it is also possible to output the plots on the same, user defined scale so that all plots are directly comparable. An example of the code for this operation in **openair** is provided in the box below.

```
# limits can be forced to 0-225 to put on same scale as max concentrations from Santon
polar.plot(santon, poll = "gr10", resolution = "fine", limits = c(0, 225),
           col = "jet", key = FALSE)
```

This would have the advantage of illustrating the relative strength of the different sources across the area but at the expense of source representation at the lower concentrations. For example, where concentrations are exceptionally high at one particular site (such as the Santon site) and the concentration scale is set to accommodate this, detail of sources at lower concentrations elsewhere (such as PM_{10} at the Keadby site) would be harder to discern.

In addition to PM_{10} (Figure 24), a selection of other maps showing NO_X, NO_2 and SO_2 has been presented using triangulated bivariate polar plots (Figures 25 to 28). Note that the Killingholme site has been plotted on its own map due to the distance from the rest of the network.

The influence of the power station is most clearly shown in Figure 24. In this map, almost all of the polar plots appear to display a clear signature that could be associated with some part of the steel works, though which part of the steel works and which processes they relate to requires further analysis as described in earlier sections.

NOx concentrations are very different and typically show the highest concentrations at low wind speeds centred around the origin of the plots, suggesting a strong contribution from local road traffic sources. This is not entirely surprising since these sources are the main reason for the location of these sites. There are a few sites that suggest an additional source of NO_X to the north and east (such as Gallagher Retail Park). Further analysis shows that these plots have been heavily influenced by a small number of very high concentrations from this wind direction. As a result, the min.bin function has been introduced into **openair** to address this issue as described earlier. NO_X concentrations measured to the east of the steel works (at Appleby and Broughton sites) suggest that contributions from sources more complex than local road traffic may be significant.

The Broughton site suggests a local road traffic source in combination with an easterly/-south easterly source from further afield and may possibly be associated with combustion sources at the steel works. Concentrations at the Appleby site are very erratic and show no strong correlation with a particular wind speed and direction but the highest concentrations measured here were at moderate wind speeds from the southerly directions, particularly from the south east and south west. The corresponding plots for NO_2 shows similar patterns as those for NOx but less well-defined patterns as a result of secondary nature of this pollutant.

These maps illustrate how several bivariate polar plots can be used in coordination to identify a specific source. This technique is most effective with simple sources and cannot conclusively single out specific sources and industrial processes in such a complex industrial environment as the integrated steel works at Scunthorpe. For example, the general location of the steel works is apparent in each map and it is clear that it is the dominant source for PM_{10}, NO_X and NO_2 and for SO_2. However, the different processes operating on site are in such close proximity that there is considerable uncertainty of the relative importance of each. For example, is the PM_{10} from the steel works from a combustion related processes emitting from a stack or from re-suspension from unmade roads resulting from site traffic, re-suspension from dry, uncovered spoil heaps or associated from stone crushing processes? In such circumstances, additional analysis techniques are required to associate trends in directional data with temporal trends or conduct analysis on specific subsets of the same data as shown on page 17.

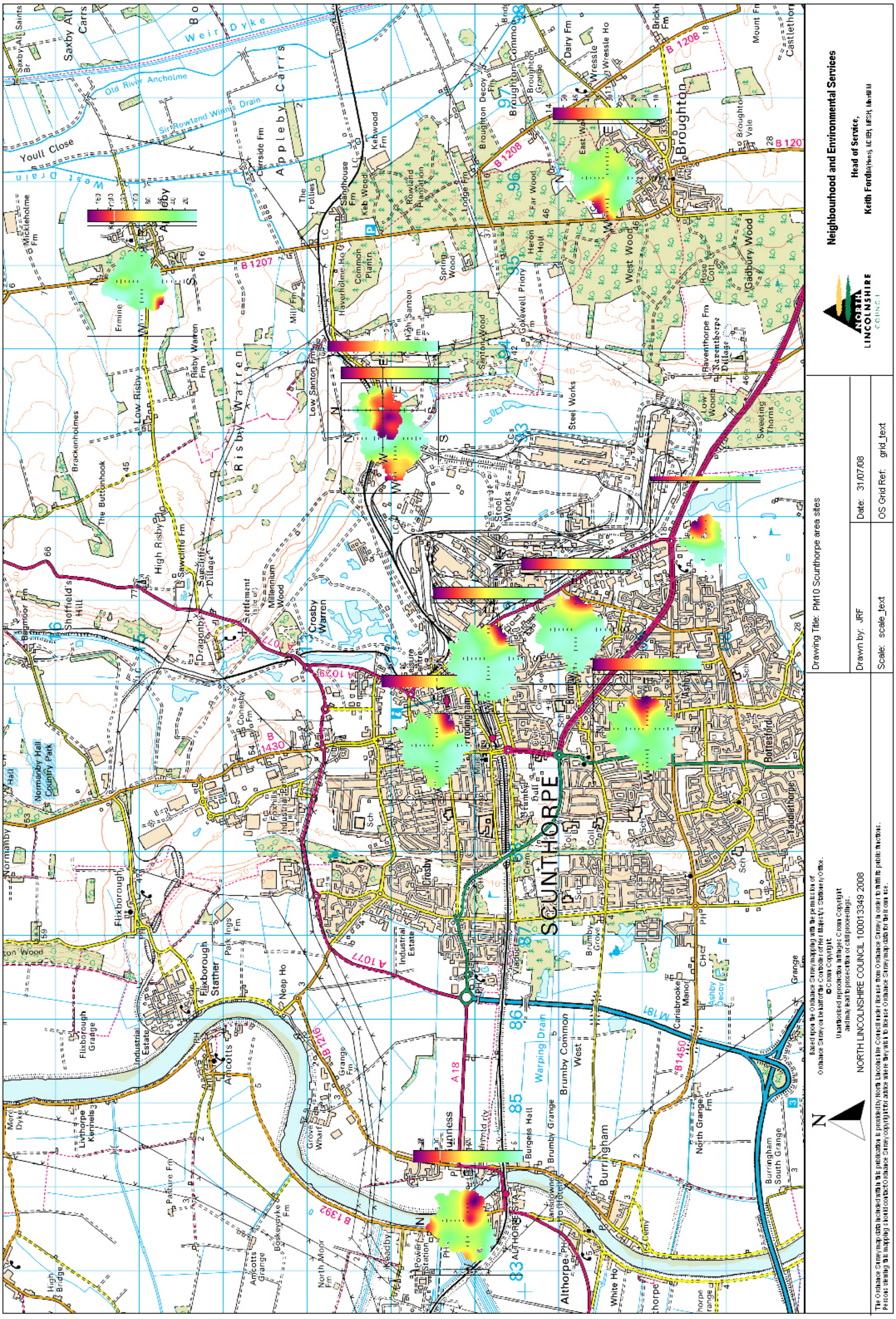

Figure 24: Map triangulation of bivariate polar plots PM_{10} Scunthorpe area sites. All bivariate plots have their own scale to emphasise features at different concentration levels.

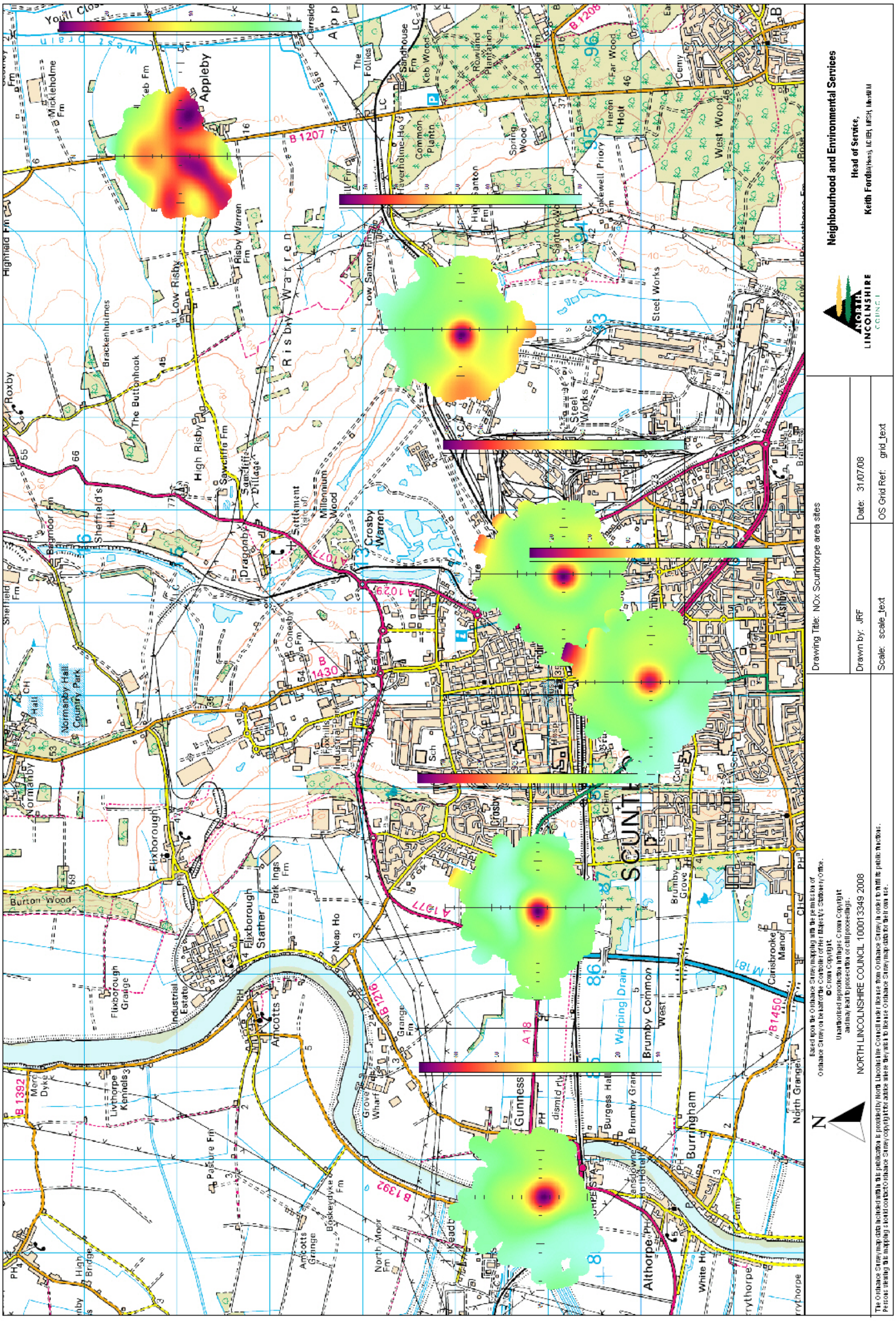

Figure 25: Map triangulation of bivariate polar plots NO_X Scunthorpe area sites. All bivariate plots have their own scale to emphasise features at different concentration levels.

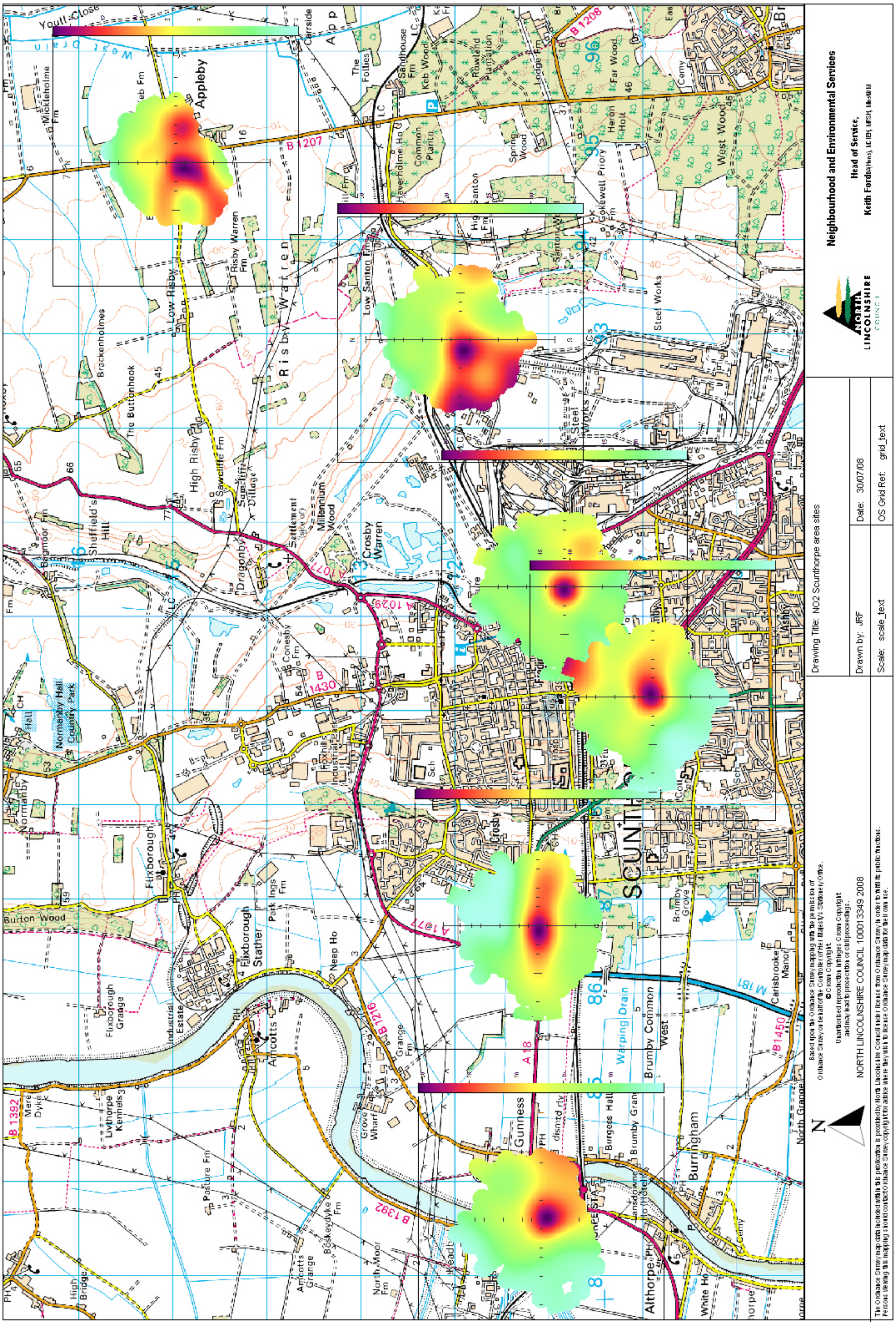

Figure 26: Map triangulation of bivariate polar plots NO_2 Scunthorpe area sites. All bivariate plots have their own scale to emphasise features at different concentration levels.

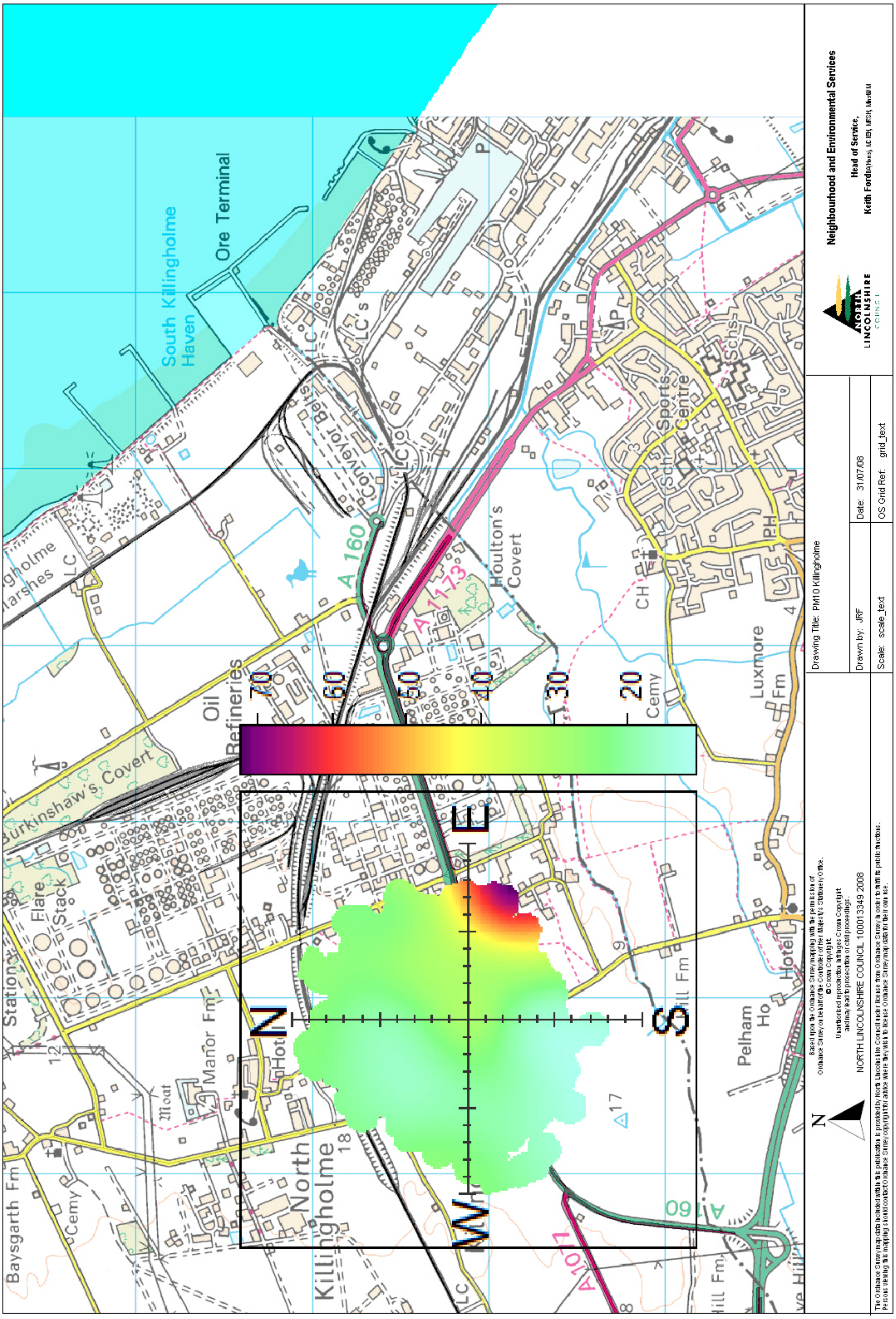

Figure 27: Map triangulation of bivariate polar plots PM_{10} at Killingholme.

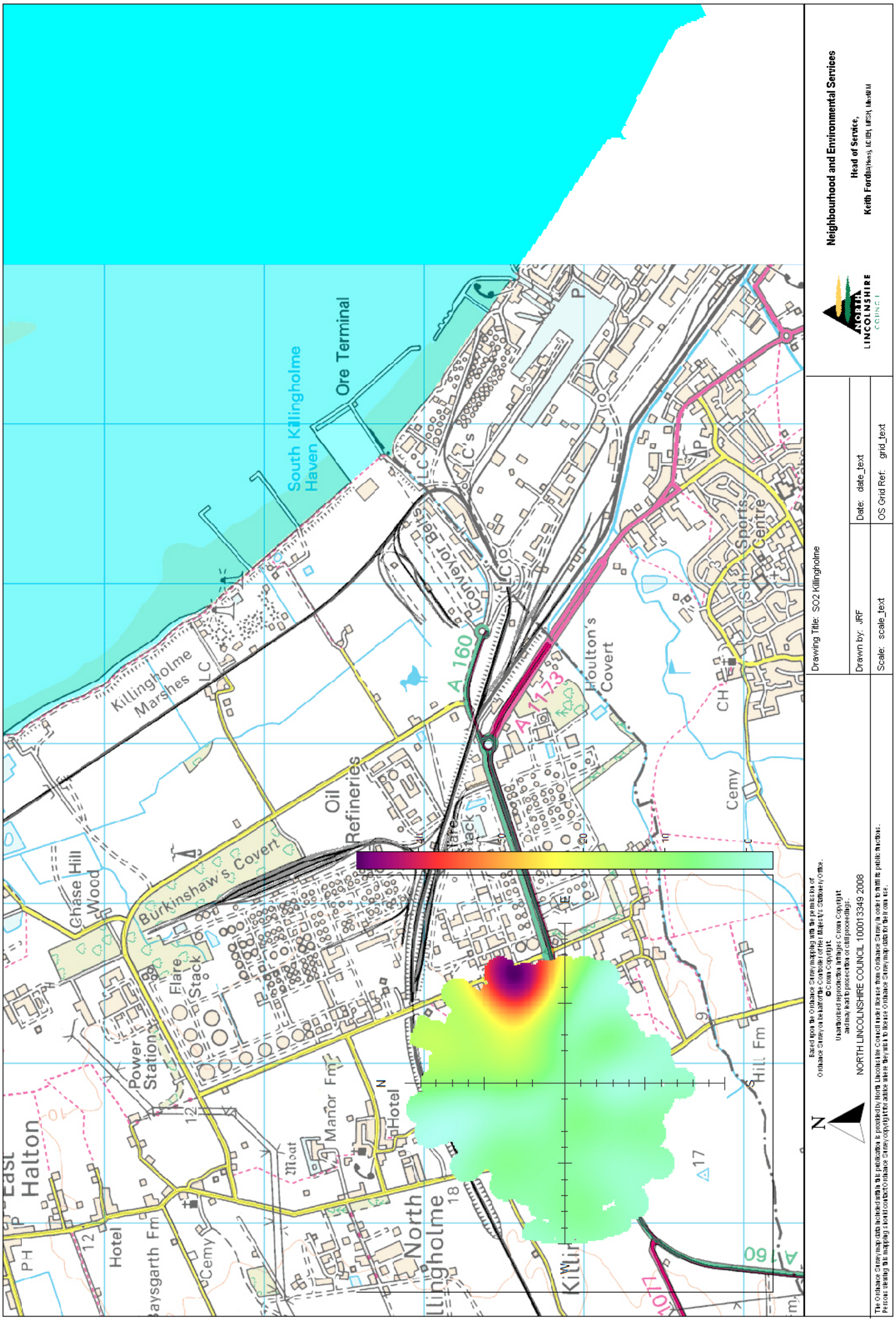

Figure 28: Map triangulation of bivariate polar plots SO_2 at Killingholme. All bivariate plots have their own scale to emphasise features at different concentration levels.

9 Further research

This case study has sought to provide examples of different analytical techniques that have been (and are still being) developed to identify sources or air pollution in North Lincolnshire (particularly around the integrated steel works owned by Corus) and to examine the various trends apparent from the monitoring data. It is recognised that not all the questions can be answered at this stage but that future development of air quality analysis tools (OpenAir) and continued monitoring across the North Lincolnshire network will allow further analysis to address these outstanding questions in due course. Specific suggestions are detailed in this section.

1. PM_{10} monitoring is the most widely spread of the pollutants measured in the North Lincolnshire network and it is clearly the most important pollutant in terms of the magnitude of concentrations measured around the steel works in relation to the AQS Objectives. However, no size fraction analysis is possible at the time of this report due to the paucity of $PM_{2.5}$ monitoring. Such data would be a considerable benefit in differentiating between the variety of industrial processes occurring there.

   As a result, we recommend that a number of OSIRIS light scattering instruments owned by North Lincolnshire Council be incorporated into the existing network as soon as this is practical, in order to provide indicative measurements of PM_{10}, $PM_{2.5}$ and PM_1. Given the high particle concentrations associated with the Santon site it would be advisable to locate several of these instruments around that site to help triangulate the contributing sources. We recommend that one of the sites is collocated with the North Lincs Santon TEOM instrument so that comparisons can be made between the instruments over the course of a day.

2. Due to the comparatively short operational periods of the sites in the North Lincolnshire network, there are currently too few data to derive long-term trends from. As a result, the temporal analysis presented in this case study has concentrated on short-term trends, particularly in support of source identification. Future work in this area might re-assess this data with more of an emphasis on long-term and seasonal trends when a longer time series of data is available. In particular, work to statistically remove the variation in pollutant concentrations due to meteorology may have been completed by then, allowing 'real' trends in air pollution to be observed. This would be of considerable benefit to North Lincolnshire Council.

3. Source attribution through data filtering would also benefit from longer time series. This work has showed that interesting features can be identified, but in some cases more data are required to fully characterise the source types.

4. Further analysis would be greatly enhanced by the availability of more specific site information e.g. source emission rates for prescribed processes, activity patterns for combustion sources etc. Such information would help link the measurement analysis with actual data on site/process use. We recognise that in obtaining and understanding such data, environmental managers at Corus and site inspectors from the Environment Agency could make an essential contribution to further research and we would welcome their cooperation on a future case study.

5. The open source air pollution project will continue to develop and new functionalities added. Given the interesting nature of air pollution in North Lincolnshire, revisiting

and extending some of this work could be very beneficial.

Acknowledgements

We would like to thank Paul Whitby, (Environment Manager of Scunthorpe Environmental Services, Corus Construction and Industrial) for organising an on-site tour of the integrated steel works prior to this analysis.

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References

Carslaw, D. C., Ropkins, K., 2009. Open-source tools for analysing air pollution monitoring data. Institute for Transport Studies, University of Leeds, version 5th Janurary 2009.

A Polar plots for all sites

Some commentary/notes on these plots is given below.

Scunthorpe Town South easterly source in both PM_{10} and SO_2 suggests industrial emissions from the steel works stacks. The SO_2 plot seems to show 2 distinct signatures - one in the south east and weaker source due easterly. It is possible that the south easterly SO_2 signature corresponds to the same source as is evident in the PM_{10} bivariate polar plot. NO_X and NO_2 concentrations are highest at this location when the wind speeds are low (less than 2 m s^{-1}). The CO plot exhibits a peculiar signature. CO and NO_2 signatures are correlated when the wind direction is from the south east across the range of wind speeds. It is peculiar that the NO_X bivariate polar plot did not identify the south easterly signature evident in the NO_2 plot. The NO_X plot suggests that there is a source further afield which affects concentrations measured at the site when the wind speeds are high and from the north east.

Appleby These plots highlight the complexity of the sources associated with the steel works indicating multiple sources in different directions. The PM_{10} plot shows two well-defined signatures, one in the north which influences measured concentrations when the wind speed is between 3–5m s^{-1}. The northerly signature does not seem correlated with increased concentrations in the other pollutants measured at the site though the south easterly source could be associated with similar increases in NO_X, NO_2 and particularly SO_2 at the full range of recorded wind speeds. In addition to the south easterly source, the SO_2 plot also shows additional sources to the east and west of the monitoring station. It is hard to pick out discreet sources of NO_X and NO_2 as concentrations in these pollutants are at the top of their range from many wind directions and across the full range of measured wind speeds. However, generally the higher concentrations occur during southerly winds and the highest concentrations when the winds were south easterly or south westerly.

Keadby NO_X and NO_2 sources affecting this site seem to be local with the highest concentrations centred on the origin of the polar plot at low wind speeds. The plot for NO_2 also shows slightly elevated concentrations from the south east at all wind speeds which is not apparent in the NO_X plot. This south easterly NO_2 feature may be associated with the PM_{10} source in the east/south east which influences concentrations the most when winds are relatively strong at 5–7m s^{-1}. The plot for PM_{10} also suggests that there may be an additional, more distant source to the north/north west, affecting the site at wind speeds of 7 m s^{-1} and above. The plot for SO_2 suggests a close proximity, well defined source to the south/south east. Maximum SO_2 concentrations occur when the wind from this direction is between 0–3m s^{-1}.

Killingholme This site is geographically separated from the rest of the network, being much further to the east of the steel works. Therefore it is less likely to exhibit evidence of the industrial processes at the Corus plant. However, east of the site is where the coast is located and the commercial harbour through which many of the raw materials for the steel works are transported. The NO_X and NO_2 bivariate polar plots suggest that the most significant source is in close proximity to the monitoring station and is likely to be local road traffic emission. There is also evidence of a more distant source to the north east affecting measured concentrations when the wind speed was high at 8 m s^{-1} and above. Both PM_{10} and SO_2 plots were dominated by single, well-defined sources -

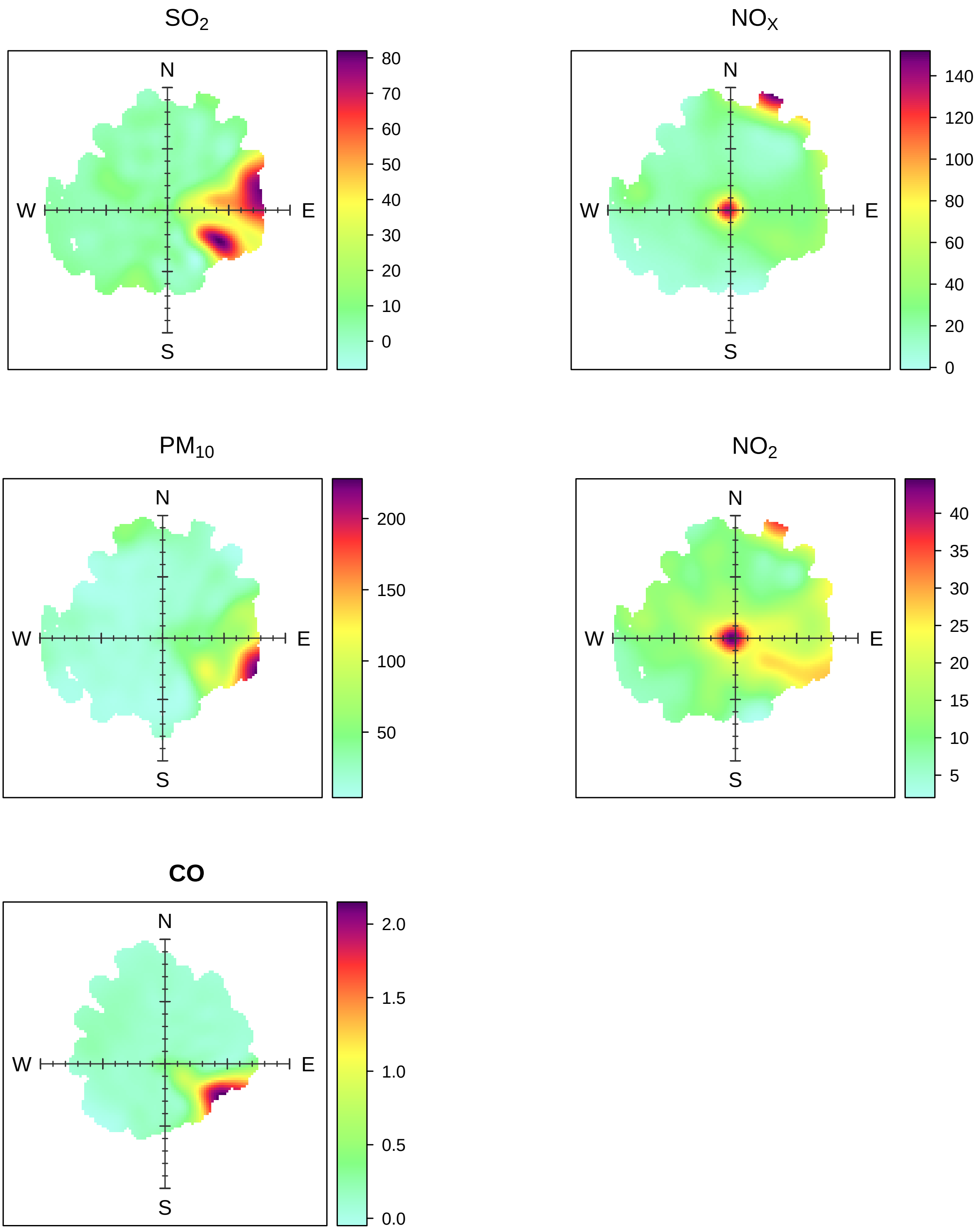

Figure 29: Polar plots for Scunthorpe Town measurements.

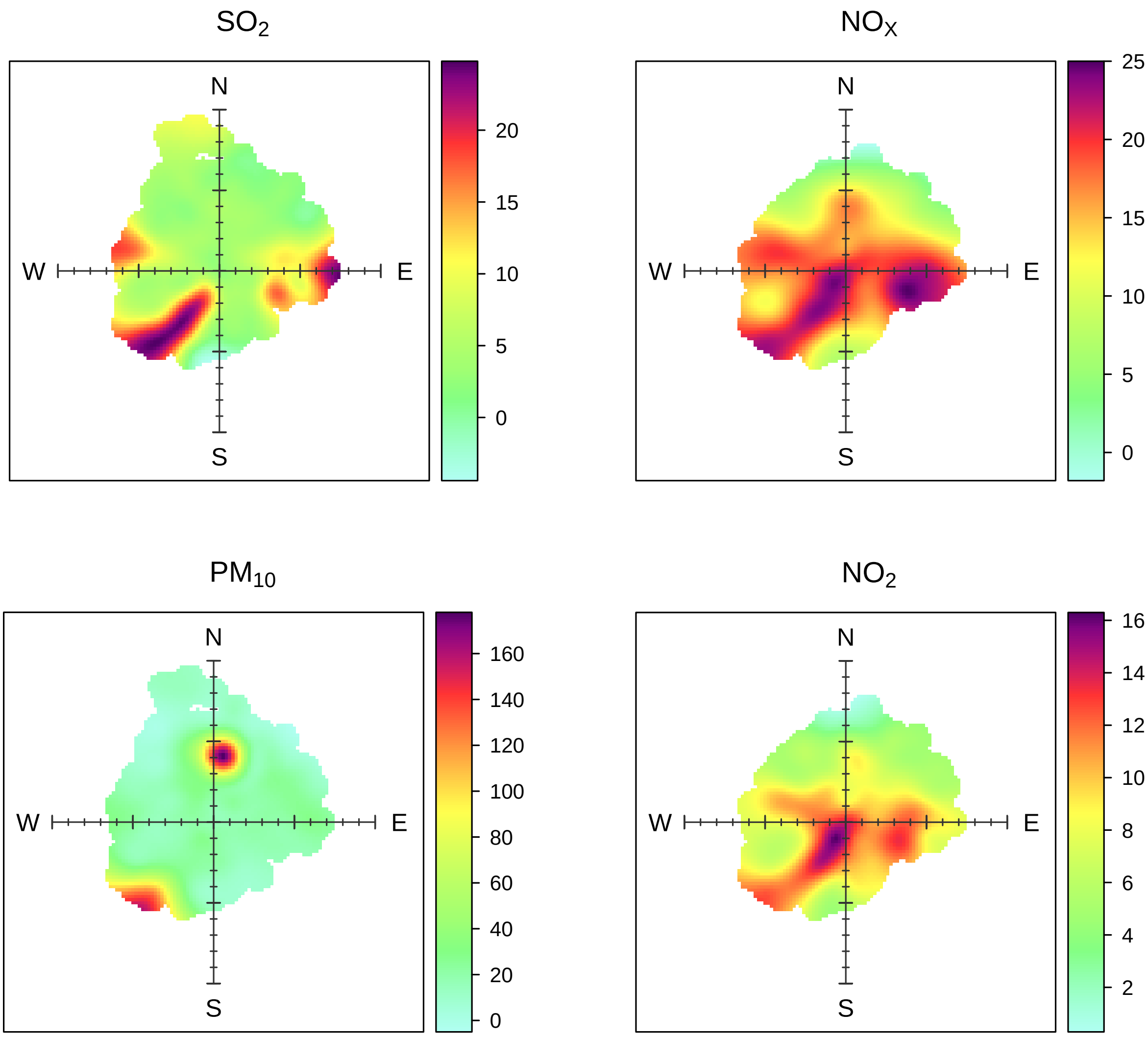

Figure 30: Polar plots for Appleby measurements.

from the east/south east for PM_{10} and from the east/north east for SO_2 when winds were 6 ms-1 and above.

Santon The highest PM_{10} concentrations in the North Lincolnshire network were measured at the Santon site. These high concentrations combined with the interesting source signatures and multiple pollutant channels available have resulted in a significant level of attention in this analysis based on this site. A notable feature of these polar plots is that there are three distinct PM_{10} signatures in the west when wind speeds are between 5–10 m s^{-1}. The SO_2 plot shows a similar situation but there is less evidence of the three distinct signatures. The NO_X and NO_2 plots suggest a localised traffic source close to the site but a source further afield to the east and particularly the south.

Gallagher Retail Park and Kingsway NO_X concentrations at these two sites have been described in more detail in Section 5.2 of the report. NO_X and NO_2 plots for both sites exhibit close proximity sources at low wind speeds which are likely to reflect the road traffic emissions that these sites have been located here to monitor. However there also appears at first glance to be an additional source to the north/north east of both

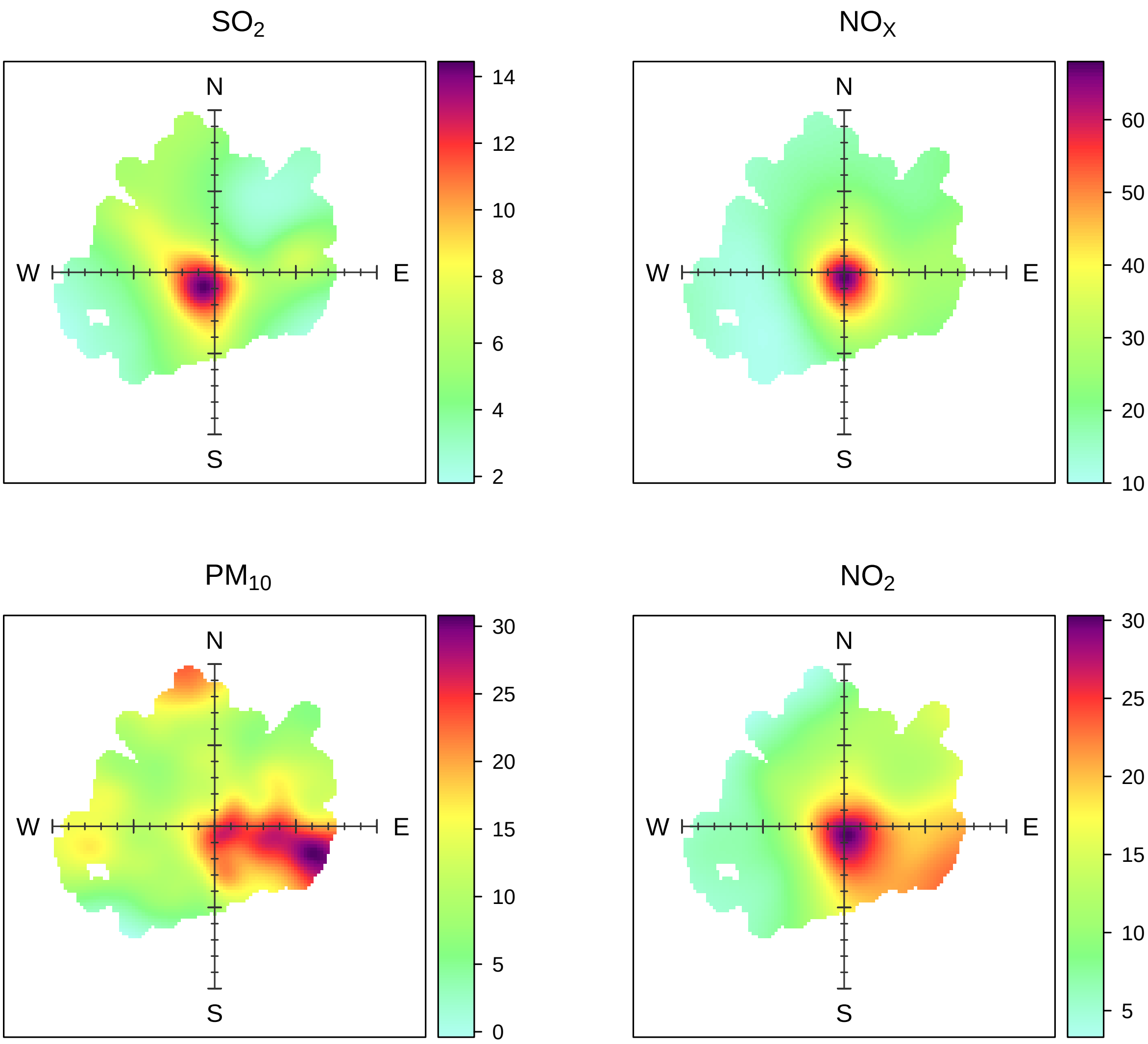

Figure 31: Polar plots for Keadby measurements.

sites. Further analysis using the min.bin function has illustrated that the Gallagher plot has been influenced by a small number of very high concentrations corresponding to met conditions at that direction and speed which are not very representative of the overall situation. By contrast, the feature displayed to the north/north east at the Kingsway House site remains after the min.bin function has been used and so we can be more confident that this apparent feature is real and representative.

Allanby Street, Appleby Village, East Common Lane, Broughton These four sites measure only PM_{10} and so analysis is more limited than at sites where there are multiple pollutant channels to interrogate. The dominant PM_{10} source at Allanby Street site appears to be east or south east of the monitoring site and affects concentrations when the wind speed is 5 m s^{-1} and above. PM_{10} sources at Appleby Village are more interesting and there appears to be a distinct source to the south west of the station which affects concentrations measured at all wind speeds. Additional, weaker sources appear to be east of the station and possibly north east also and affect the measured concentrations when wind speeds are 4 m s^{-1} and above. East Common Lane is dominated by a well-defined source due east when winds are 5 m s^{-1} and above.

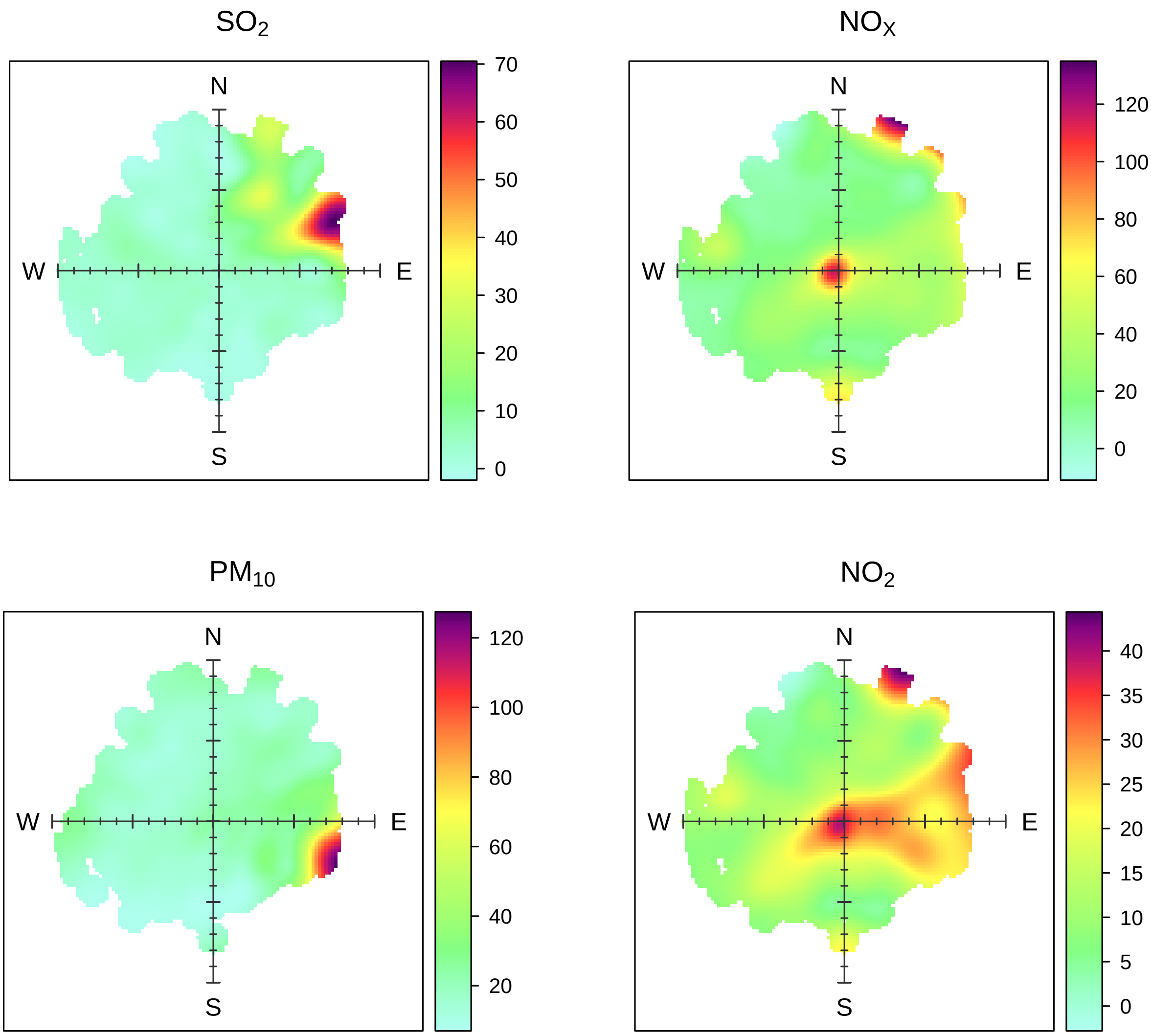

Figure 32: Polar plots for Killingholme measurements.

Sources affecting the Broughton site are from the west/ north west and influence measured concentrations most during wind speeds of 5 m s^{-1} and above.

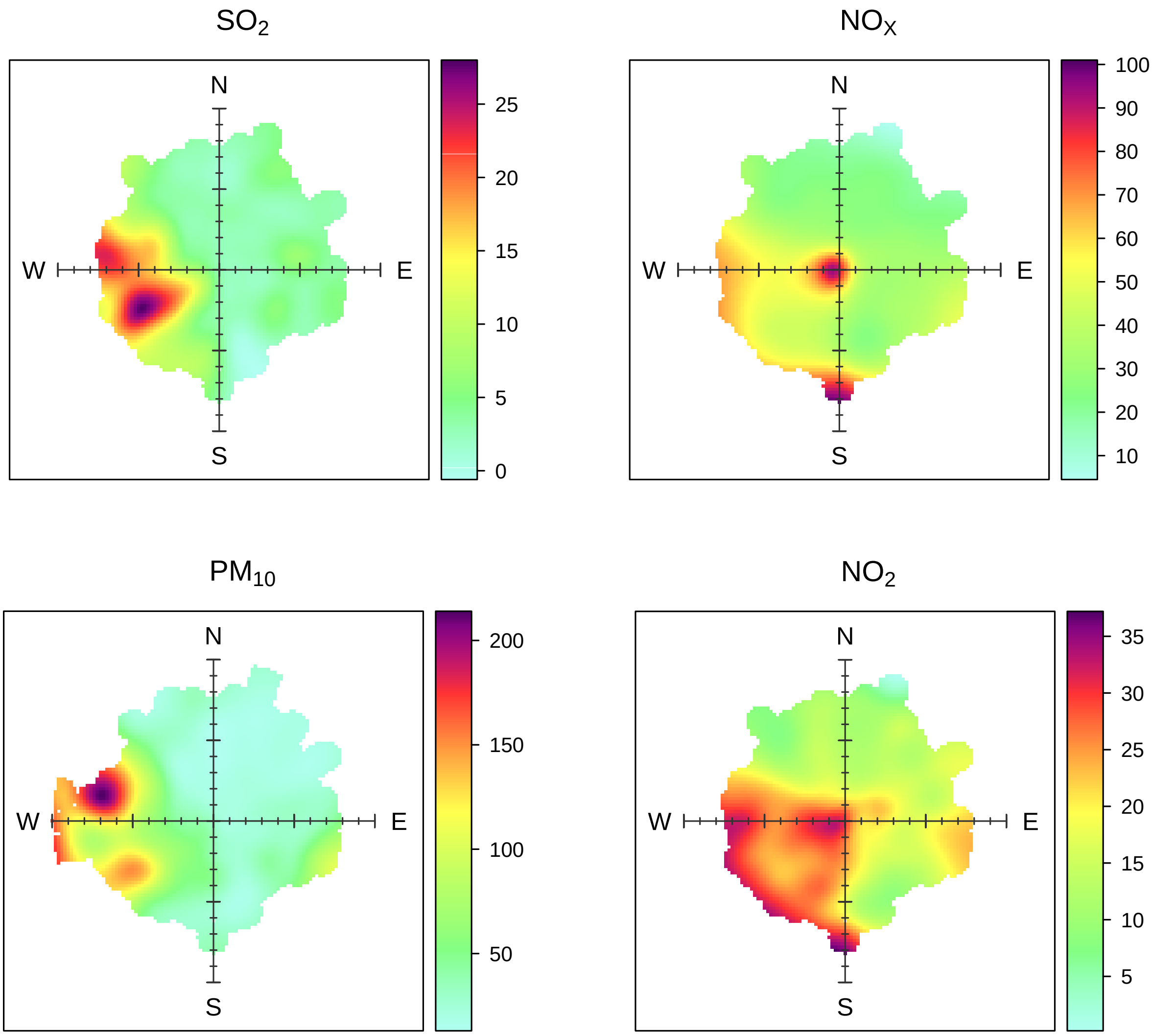

Figure 33: Polar plots for Santon measurements.

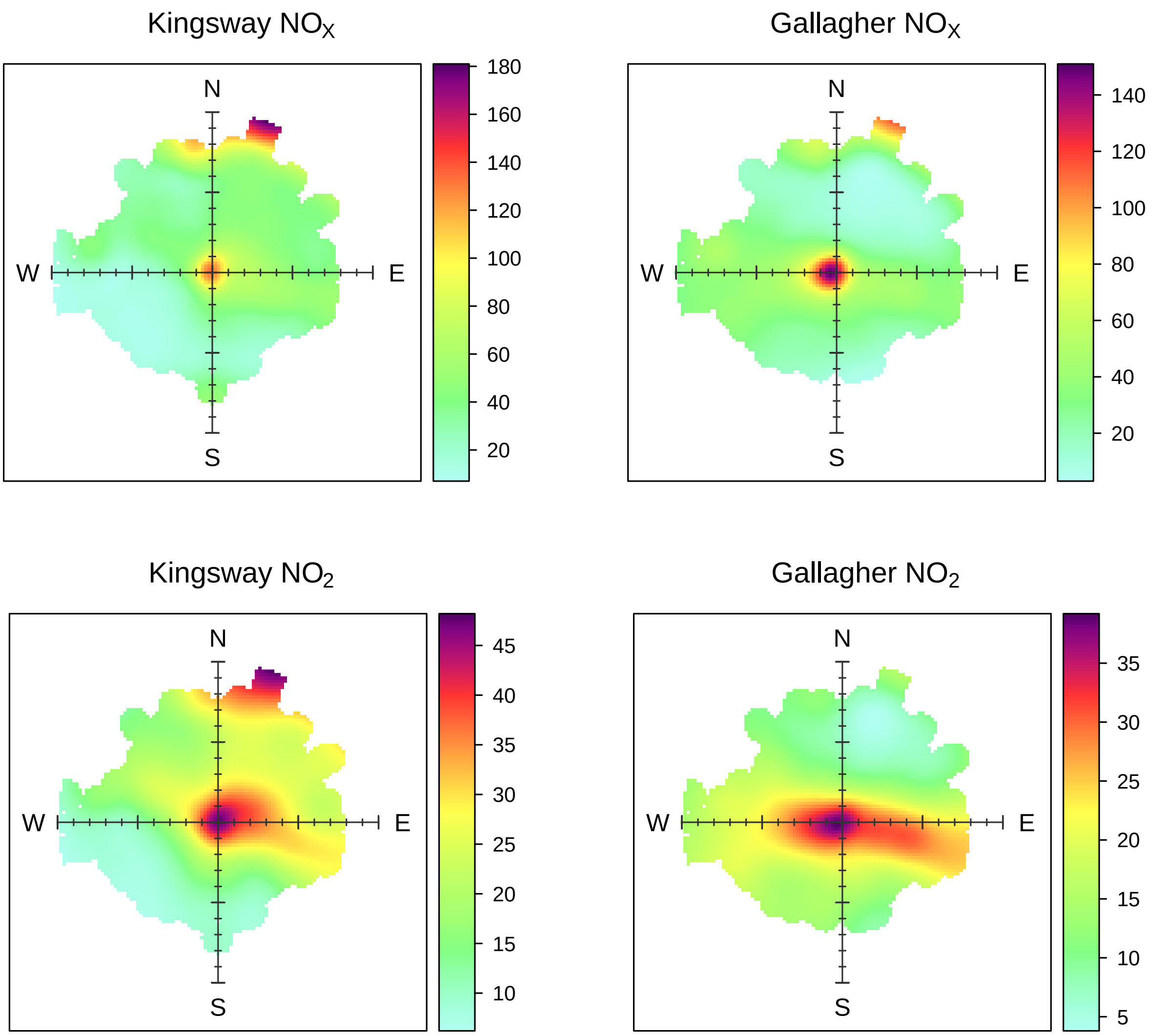

Figure 34: Polar plots for Gallagher and Kingsway measurements.

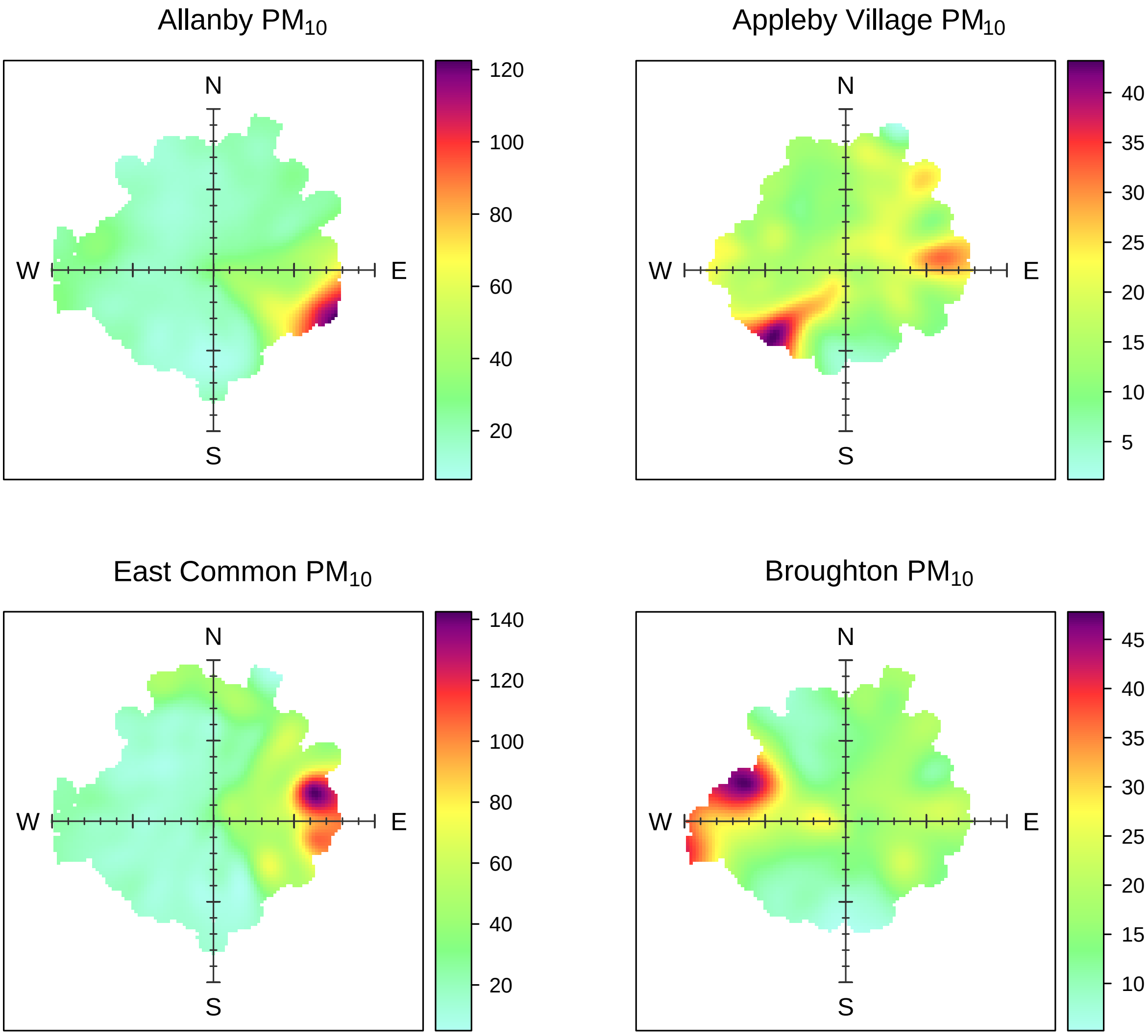

Figure 35: Polar plots for Allanby, East Common Lane, Appleby Village and Broughton PM_{10} measurements.