Improving short-term air quality: a trial protocol for SO$_2$ from power stations

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Abstract

On January 1st 1998 three UK power companies began to investigate a novel system designed to reduce the possibility of coal-fired power stations causing the new 100 ppb 15 minute ambient air quality SO$_2$ standard being exceeded. Three 2000 MW power stations were selected to take part in a one year trial. Although the trial did not involve any actual changes to operation of any power station, it was designed to reflect in real time what would happen were such a system to be operated in reality.

The protocol centred around the use of meteorological forecast data and dispersion modelling to predict exceedances of the air quality standard and hence enable changes to power station operation to take place.

A large amount of data has now been collected and analysed. Factors influencing the success of the system in eliminating air quality problems have been investigated. These include the influence of the accuracy of the meteorological forecast data on the accuracy of the model predictions and the effectiveness of the operational decisions in improving air quality.

Comparison of the predicted number of air quality exceedances with the trial system in operation compared to the predicted number when power station operation is not constrained indicates that this method is not effective as a method for air quality management.

This paper will present the results of the analyses which lead to this conclusion.
Introduction

In 1996, upon the recommendation of the Expert Panel on Air Quality Standards, the UK Department of the Environment (DoE) adopted a new ambient air quality standard for SO\(_2\) of 100 ppb as a 15 minute mean. An objective was subsequently set to reduce SO\(_2\) ground level concentrations in the UK such that the 99.9th percentile of 15 minute means at all locations does not exceed 100 ppb by 2005.

At the request of the Environment Agency, the operators of coal-fired power stations undertook some preliminary modelling studies to establish the extent to which such power stations might cause exceedances of the 100 ppb SO\(_2\) standard. From these studies it was concluded that these sources could cause exceedances of the standard at the 99.9th percentile level when operating at the high load factors typical at that time.

This precipitated a series of studies by the generating companies into circumstances under which high SO\(_2\) ground level concentrations might result from plant operation and whether or not it might be possible to manage local air quality in an effective manner by predictive modelling using forecast meteorology and subsequent operational action: a management protocol for SO\(_2\).

In this paper, the results of the studies are presented which culminated in three power companies running a year long trial of an SO\(_2\) management system.

Objectives of studies

The first objective of the study was to identify, and if possible categorise, the meteorological conditions which would lead to exceedances of the SO\(_2\) standard by power stations.

The second objective was an assessment of the accuracy of meteorological forecasts to predict the meteorological parameters relevant to dispersion and the limitations this would impose on a management protocol.

Finally, the conclusions of the desktop analyses were used to design a protocol for SO\(_2\) air quality management and a ‘real time’ simulated trial undertaken at three coal-fired power stations.

Occurrence of ground level concentrations exceeding 100 ppb

The dispersion model ADMS v2.1 (Atmospheric Dispersion Model System) was set up to simulate 2000 MW coal-fired power stations in different parts of the UK in order to assess time of day and seasonal dependence of the occurrence of ground level concentrations of SO\(_2\) exceeding 100 ppb, and to establish the types of meteorological conditions which lead to such exceedances.

Using meteorological data and other input for a variety of locations around the UK, it was established that there were three broad categories of meteorological conditions that gave rise to ground level concentrations of SO\(_2\) greater than 100 ppb:
- Low (convective) boundary layer (<500 m)
- Convective with boundary layer >500m and h/L_m < -2 (h = boundary layer height and L_m = Monin-Obhukov length)
- Windy (wind speed > 8.2 ms⁻¹ and h/L_m > -2).

An examination of the distribution of meteorological conditions predicted to cause exceedances at full load with season and time of day showed that almost all the exceedances occurred during daylight hours. This is primarily because the boundary layer depth is much lower at night with the plume being emitted into the atmosphere above it. The exceedances can occur throughout the day and do not show any pronounced seasonal dependence except the obvious correlation between reduced convective activity in winter and the reduction in exceedances due to highly convective conditions.

Figure 1 shows the frequencies of occurrence of exceedances of the air quality standard as a function of meteorological category and distance downwind (power station on full load). Exceedances due to very windy conditions tend to occur within 8 km of the power station whereas the model predicts that those due to highly convective conditions or low boundary layer conditions tend to occur over much greater distances.

The next stage was to develop an understanding of the robustness of UK Meteorological Office predictions as a surrogate for actual measured meteorological parameters in modelling the dispersion of a plume.

![Figure 1: Number of 100 ppb exceedances predicted for a 2000MW power plant at full load as a function of weather category and distance downwind.](image-url)
Predictions of the meteorological parameters required by ADMS were obtained from the UK Meteorological Office's Mesoscale model. This model is run from 6 am daily to provide hourly predictions of meteorological parameters until 12 noon the following day. In this study data were used from 12 noon on the day of the model run until 12 noon on the following day (i.e. predictions made between 6 and 30 hours in advance).

Predictions of hourly average values of wind speed, wind direction, cloud cover, temperature, Pasquill stability class and boundary layer depth were provided, together with their actual values at the UK Meteorological Office measurement site.

The correlation coefficients between the predicted and measured data were determined for each of the above parameters. The predicted and actual parameters were found to be significantly correlated at the 0.1% level in all cases. The predictions for wind direction and temperature were clearly better than those for other parameters. Those for cloud cover were found to be the poorest.

A comparison of ADMS modelled hourly average concentrations at ground level for unit emission concentration using predicted and actual input meteorological parameters is shown in figure 2. Again, the correlation is significant at the 1% level. However, the correlation coefficient, $R^2$, is very low at 0.33, and even less, at 0.05, if the correlation at a specific point is determined. Therefore, it can be concluded that, on an hour-by-hour basis the prediction of exceedance is poor.

Figure 3 compares predictions for a typical 2000 MW power station based on predicted and actual meteorology for exceedances of the EPAQS equivalent 1 hour value of 80 ppb and WHO 1 hour guideline (122 ppb over 1 hour) for SO2. The number of occasions when the forecast meteorological data and actual meteorological data both led to an exceedance is seen to be relatively small.
Figure 2: Scatter plot of predicted ground level concentration of $\text{SO}_2$ using forecasted meteorology versus predictions using actual meteorology.

Figure 3: Percentage of time that exceedances of 100 ppb $\text{SO}_2$ standard using actual meteorology was also predicted using forecast meteorology.
Overall, it was concluded that prediction of key meteorological parameters, (particularly cloud cover which is an important input parameter to models such as ADMS) from 6 to 30 hours in advance was found to be poor. As a result, environmental air quality management based on concentration predictions from dispersion models on an hour-by-hour basis, is unsatisfactory, as on most occasions either unnecessary action will be taken to control emissions or pollution incidents will be missed.

A broader approach might involve taking action on a daily timescale rather than on an hour by hour timescale. A noticeable improvement in coincident predictions of days during which an exceedance occurred compared to those for the hour-by-hour comparison was found.

Therefore, it was concluded that, for the management of pollution incidents using model predictions based on meteorological forecast data to stand any chance of being effective, the timescale for action would have to be the whole day rather than for individual hours and to be irrespective of location. This timescale also corresponded more closely with the time taken to change sulphur emissions by switching coal supply.

Having determined the basic potential for an SO\textsubscript{2} protocol, a one year long trial was designed to study the feasibility in detail.

An in-depth trial of a method of air quality management for SO\textsubscript{2} was undertaken over a one year period (Jan-Dec 1998) at three major UK coal-fired power stations. The three power stations selected for the trial (and their owners at the time) were Ferrybridge C (PowerGen UK plc), West Burton (TXU Europe Power, formerly Eastern Generation Ltd) and Eggborough (National Power PLC).

The process involved using forecast meteorological data and a plume dispersion model to predict whether or not exceedances of air quality standards might occur the next day or later during the same day as the predictions.

Although the trial did not involve any actual changes to operation of any power station, it was designed to closely follow in real time what would happen were such a system operated in reality.

Key components of the system were:

- A dedicated computer (running the ADMS dispersion model and software to input data automatically) which predicts maximum SO\textsubscript{2} emissions or electricity generating capacity for each day and the following day.
- A daily Met Office Unified Model forecast of parameters for use in the ADMS dispersion model.
- Computer terminals in the Companies’ Energy Management Centres to enable load/fuel change decisions to be made each day based on the predictions.

The exact way the trial was conducted varied in detail between companies. Figure 4 is a schematic diagram for the PowerGen arrangement.
The key part of the trial was the computer system which forecast the generation constraints that the environmental air quality considerations placed on the operation of the power station.

At 0600 GMT each day, the system dialled up the Meteorological Office and downloaded 60 hourly forecasts of the meteorological parameters required by the dispersion model.

Once the meteorological data had been downloaded the program ran the ADMS dispersion model for a series of power station loads for each hour of the meteorological dataset downloaded.

The hours for which predictions were made were 0600 to 1800 for the next day and 0800 to 1800 on the day. It had been established that ADMS did not predict any exceedances outside these hours from power stations.

![Schematic Diagram of the PowerGen Air Quality Protocol Trial](image)

Figure 4: Schematic diagram of main components of SO$_2$ Trial Protocol.

The model predicted ground level concentrations of SO$_2$ on a 40x40 km square grid at a resolution of 1.5km, centred on the power station.

The maximum generation for the day and the day ahead were then determined based on the sulphur content of the coal stocks available.

The potential constraints to operation of the power station were then passed on to the company Energy Management Centre by intranet or e-mail.

The EMC were normally given 2 options – to burn standard sulphur content coal, with reduced generating capacity if necessary, or to switch to low sulphur coal, which might allow the generating capacity to be maintained.
This procedure continued each day for one year. The recorded data were then analysed and the ADMS predictions with the modified ('Trial') generation and SO\textsubscript{2} emissions compared with the predictions using the actual generation and actual SO\textsubscript{2} emissions (in both cases actual meteorological data recorded at the nearest UK Meteorological Office weather station were used).

By way of an example, the spatial distribution of ADMS predicted event hours in the vicinity of one of the power stations is presented in figure 5. In figure 5 the predictions are for the actual power station generation and actual meteorological data. The result of actual implementation of the Protocol was simulated using the data from constrained generation brought about by the trial with the actual meteorological data measured at the weather station.

**Number of Event Hours using Actual Generation and Fuel Sulphur Content Data.**

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<th>-5000</th>
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Figure 5: 40x40 km grid showing number of hours during year that an exceedance of the 100 ppb SO\textsubscript{2} standard was predicted around one of the power stations without the trial protocol in operation.

SO\textsubscript{2} monitoring sites were in operation at a number of locations around the power stations taking part in the trial and data from these sites were compared to...
the predicted ground level concentrations. As an example, there was a monitoring site 4.5km ENE of the power station whose impact on local air quality is predicted in figure 5. This is close to the position of maximum predicted impact.

An analysis of the data from this site showed that, when the wind was blowing from the direction of the power station (assumed to be 240-270° N), the number of hours during which there was at least one 15 minute exceedance of 100 ppb was 32. These occurred on 23 different days during the trial. If the Protocol had been in operation, 11 of the event hours actually measured would have been predicted and 17 of the event days. This confirms the supposition that it is easier to predict that an exceedance will occur at some time during a day than to be more precise about the actual hour of occurrence.

(An ‘event day’ is defined as a day when ADMS predicted an exceedance of the 100 ppb SO\textsubscript{2} standard at any receptor point at any time during the day. An ‘event hour’ is defined as an hour during which ADMS predicted at least one 15 minute exceedance of 100 ppb).

Comparison of the predicted number of exceedances (10-46) with the actual measured number (32) suggests that the model predicts the number of event hours over the period of a year reasonably well. However, the timing of the events is not well predicted.

A series of tests were applied to the data from the trial to determine the degree to which it met the objectives, see table 1.

It would be hoped that the hit rate will be higher than the miss rate, and that the success rate will be higher than the failure rate for a successful trial.

It would be expected that the Random Chance Rate would be lower than the Trial Success Rate if the protocol is to have any hope of succeeding.

Table 1: Summary statistics of the ability of the Trial Protocol to manage air quality.

<table>
<thead>
<tr>
<th>Test</th>
<th>PowerGen</th>
<th>National Power</th>
<th>Eastern Generation</th>
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<tr>
<td></td>
<td>Day Result</td>
<td>Hour Result</td>
<td>Day Result</td>
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<tr>
<td>Hit Rate</td>
<td>0.68</td>
<td>0.75</td>
<td>0.53</td>
</tr>
<tr>
<td>Miss Rate</td>
<td>0.32</td>
<td>0.25</td>
<td>0.47</td>
</tr>
<tr>
<td>Success Rate</td>
<td>0.50</td>
<td>0.14</td>
<td>0.31</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>0.47</td>
<td>0.57</td>
<td></td>
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<tr>
<td>Action Rate</td>
<td>0.60</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>Random Chance</td>
<td>0.25</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>
Footnote: The Hit (Miss) Rate can be defined as:

- Event Days(hours) Saved(Missed)
- Event Days(hours)

The Success Rate as:
- Event Days(hours) Saved
- Action Days(hours)

The Action Rate as:
- Action Days
- Days in Trial

The Failure Rate as:
- Unnecessary Action Days
- Action Days

The Random Chance Rate as:
- Number of Action Days
- Number of Event Days
- Number of days in period or
- Number of Days Trial Ran
- Action Rate
- Event Rate

From the various tests it can be seen that the trial successfully prevents about 60% of all events (averaged over the three power stations), and misses about 35% completely (miss rate). The cost of this is a very high action rate, especially during the summer when most days required action.

For the trial as a whole the success rate was only marginally higher than the failure rate, so for every action which prevented an event, another was taken which was unnecessary.

The above tables show that the protocol is initiating action far too often to be an effective tool for use against local pollution incidents. The costs of implementing such a system due to loss in generation and low sulphur coal, would be as large as the costs of retro-fitting of flue gas desulphurisation plant.

**Conclusions**

- Predicting the occurrence of days during which a power station causes a ground level concentration of SO\(_2\) to exceed the UK national air quality standard concentration for at least 15 minutes somewhere in the vicinity is subject to large uncertainties.
- Notwithstanding the inaccuracies of the physical dispersion algorithms implicit in any predictive model used, the accuracy of such a prediction also depended strongly on the accuracy and applicability of the meteorological data input. For example the best available forecast data (from the UK Meteorological Office) limits the correct day-in-advance prediction of exceedances of the air quality standard to about 50%.
- This makes a system of local air quality management based on forecast meteorological data and computer modelling very inefficient and expensive.