



## Total SO<sub>2</sub> Emissions from Power Stations and Evaluation of their Impact in Kuwait Using a Gaussian Plume Dispersion Model

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**Abstract:** In Kuwait, most of the power stations use fuel oil as the prime source of energy. The sulphur content (S%) of the fuel used as well as other factors have a direct impact on the ground level concentration of sulphur dioxide (SO<sub>2</sub>) released by power stations into the atmosphere. The SO<sub>2</sub> ground level concentration has to meet the environmental standards set by Kuwait Environment Public Authority (KEPA). In this communication we present results obtained using the Industrial Sources Complex Short Term (ISCST3) model to calculate the SO<sub>2</sub> concentration resulting from existing power stations in Kuwait assuming zero background SO<sub>2</sub> concentration and entire reliance on Heavy Fuel Oil. 1, 2, 3 and 4S% scenarios were simulated for three emission cycle cases. The computed annual SO<sub>2</sub> concentrations were always less than KEPA standards for all scenarios. The daily SO<sub>2</sub> concentrations were within KEPA standards for 1S% but violated KEPA standards for higher S%. In general, the concentrations obtained from the combined hourly and seasonal cycle were the lowest and those obtained from the no cycle case were the highest. The comparison between the results of the three cycles revealed that the violation times cannot be solely attributed to the increase in emissions and the meteorological conditions have to be taken into consideration.

**Key words:** Air pollution, ISCST3, sulphur dioxide

### INTRODUCTION

In the last century, advancement in industrialisation and medical care has elevated the living standards and increased the population and their life expectancy. This development has resulted in great constrain on the environment in the form of increased atmospheric pollution, global climate change, etc. Amongst the major atmospheric pollutants is sulphur dioxide (SO<sub>2</sub>). SO<sub>2</sub> emissions from power stations account for 69% of total emissions, whilst 13% comes from burning fuel in manufacturing industries and construction. According to Hamzeh<sup>[1]</sup>, the World Bank estimates that the transport sectors' contribution to global SO<sub>2</sub> emissions is between 2-6%. With this in mind, the importance of capping the SO<sub>2</sub> emissions from power stations is indisputable. In order to plan the required fuel quality for the existing and planned power stations, it is imperative to consider the variation of air pollutant concentrations due to different types of fuels as well as the behaviour of these pollutants in response to the prevailing meteorological conditions. The presented work examines the effect of the load cycles on the ground level concentration of SO<sub>2</sub> as well as the effect of S%.

Boix<sup>[2]</sup> have used vectorial model to assess the influence of local breeze and other meteorological parameters on the ground level concentrations of SO<sub>2</sub> and particulate matters in the urban area of Castellón-Spain. They have reported a decrease in the concentrations of SO<sub>2</sub> and particulate matters in winter months due to strong prevailing wind while measured concentrations in summer were higher than recorded in winter months. A decrease in concentrations was noticed in hot days in winter while no such phenomenon was observed in summer.

Honaganahalli and Seiber<sup>[3]</sup> have compared Industrial Source Complex Short Term 3 (ISCST3 - a plume dispersion model) with CALPUFF (a puff dispersion model) for several fumigated fields serving as source for methyl bromide (CH<sub>3</sub>Br) in the Salinas Valley-California. The simulated results were compared with the field measurement from 11 sites on the adjacent mountains, valley floor and at Pacific Ocean coast over a 4 days period. For Seiber *et al.*<sup>[4]</sup> flux values, ISCST3 model under-predicted concentrations for 76% of data (the predicted concentrations were 66% of those measured) while the CALPUFF model also under-predicted 67% of observations (the predicted

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concentrations were 84% of the measured). For Yates *et al.*<sup>[5]</sup> flux values, ISCST3 model over-predicted concentrations by a factor of 2 for 67% of data and CALPUFF over-predicted concentrations by a factor of 1.6 for over 50% of data.

Other researchers, e.g. Barna and Gimson<sup>[6]</sup>, Levy *et al.*<sup>[7]</sup> and Zhou *et al.*<sup>[8]</sup> have evaluated the performance of CALPUFF for different pollutant sources including home heating, motor vehicles, power plants and general industries. Their results will not be discussed here due to space limitations.

**The power stations in Kuwait:** The existing five power stations in Kuwait (Fig. 1) are: 1) Doha East (DE), 2) Doha West (DW), 3) Subiya (SUB), 4) Zour South (ZS) and 5) Shuaiba South (SH). The chimneys' design in SUB, ZS, DW is identical as each station has two chimneys each of which contains four stacks. DE differs slightly as it has two chimneys, one of which has four stacks and the other has three stacks. Each station was represented by a number of point sources equal to the number of chimneys in the station. This was done based on the recommendation of The<sup>[9]</sup> and is similar to presentation of sources by Al-Ajmi and Marmoush<sup>[10]</sup>, Al-Ajmi and Marmoush<sup>[11]</sup>, Al-Awadhi *et al.*<sup>[12]</sup>, Ramadan *et al.*<sup>[13]</sup>, Ramadan *et al.*<sup>[14]</sup> and Ramadan *et al.*<sup>[15]</sup>.

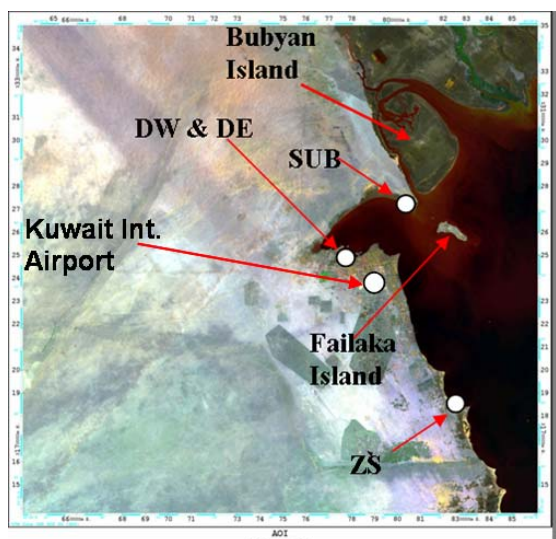


Fig. 1: Power stations in Kuwait

The diameter for the point source was the equivalent diameter to the three/four stacks in the chimney. The exit speed is considered the same but the emission rate is the sum of that for the four stacks. The stacks locations, elevations and diameters and the exit

speeds and temperatures and the peak emission rates are listed in Table 1. The SO<sub>2</sub> emission rate for each of the power stations was expressed as a function of the sulphur content (S%) in the liquid fuel and the specified fuel consumption rate. The seasonal-hourly cycle of power generation was based on information provide by the National Control Centre–Ministry of Energy (NCC–MOE).

**The numerical model:** The Industrial Source Complex - Short Term (ISCST3) dispersion model is an air-quality model based on the Gaussian-plume simplification of the diffusion equation that assumes time independence in the input meteorology and source concentration. The ISCST3 algorithm calculates concentrations of non-reactive pollutants and/or deposition fluxes from a wide variety of sources. The ISCST3 dispersion model which was designed to support the US-EPA's regulatory modelling options does not take into account changes due to photo-reactions. The model is capable of predicting results within 25km radius from the point source, hence "Short Term".

The model was run using 1999-2003 meteorological data collected at Kuwait International Airport (Fig. 1) and it was assumed to be representative of the meteorological data of the entire State of Kuwait. (Fig. 2) shows the windrose plot for 1999-2003. The stability class was defined on the basis of Pasquill categories<sup>[16]</sup>. The rural and urban mixing heights as well as the friction velocity, Monin-Obukhov length and roughness length at the application site were included in the meteorological data files used.

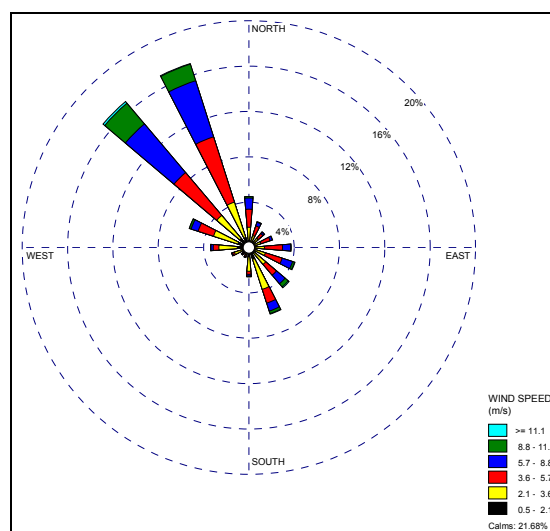


Fig. 2: Hourly wind data for Kuwait (1999-2003)

Table 1: Stacks locations, elevations and diameters and the exit speeds and temperatures and the peak emission rates used in the model

| Power Station | No. of stacks in Chimney | H (m) | T (K) | V (ms <sup>-1</sup> ) | D m   | Equivalent D m | Emission Rate per stack (gs <sup>-1</sup> ) | Equivalent Emission rate | X      | Y       |
|---------------|--------------------------|-------|-------|-----------------------|-------|----------------|---|--------------------------|--------|---------|
| DW1           | 4                        | 190   | 408   | 23.719                | 4.238 | 8.656          | 409.379968                                  | 1637.519872              | 769685 | 3250890 |
| DW2           | 4                        | 190   | 408   | 23.719                | 4.238 | 8.656          | 409.379968                                  | 1637.519872              | 769716 | 3250550 |
| DE1           | 4                        | 190   | 408   | 18.934                | 3.488 | 6.976          | 219.268391                                  | 877.0735645              | 770608 | 3251030 |
| DE2           | 4                        | 190   | 408   | 18.934                | 3.488 | 6.041          | 219.268391                                  | 657.8051733              | 770629 | 3250795 |
| SUB1          | 4                        | 193   | 423   | 23.719                | 4.500 | 9.000          | 286.727860                                  | 1146.911444              | 802927 | 3274322 |
| SUB2          | 4                        | 193   | 423   | 23.719                | 4.500 | 9.000          | 286.727860                                  | 1146.911444              | 802917 | 3274149 |
| SZ1           | 4                        | 192   | 403   | 23.719                | 4.300 | 8.600          | 422.654922                                  | 1690.619692              | 828062 | 3180719 |
| SZ2           | 4                        | 192   | 403   | 23.719                | 4.300 | 8.600          | 422.654922                                  | 1690.619692              | 827843 | 3180701 |

Table 2: Ambient air quality standards for residential areas in Kuwait

|                     | Hour* |                   | Day** |                   | Year |                   |
|---------------------|-------|-------------------|-------|-------------------|------|-------------------|
|                     | ppb   | µgm <sup>-3</sup> | ppb   | µgm <sup>-3</sup> | ppb  | µgm <sup>-3</sup> |
| SO <sub>2</sub> *** | 170   | 444               | 60    | 157               | 30   | 80                |

\* Average hour not to occur more than twice during the period of 30 days on the same site

\*\* Daily average (24 hours) should occur once during the year

\*\*\* Should apply in residential dominated areas that lie on the border of industrial areas

The model was executed using three uniform square grids each with 441 grid points as receptors. The centre of the three grids coincided with the centroid point for the station(s) considered.

The first uniform grid covered an area of 50km×50km with grid spacing of 2.5km. Second and third finer grids (areas of 20km×20km and 10km×10km with grid spacing of 1km and 0.5km respectively) were superimposed over the first coarse grid for accurate evaluation of the concentrations around the centroid of the power stations. A uniform terrain elevation grid of 382 by 332 grid points at 500m spacing covering a total area of 190.5km by 165.5km was used in ISCST3 calculations. The main assumptions made can be summarised as:

- \* The background SO<sub>2</sub> level (due to refineries, transportation, other industries, etc) is assumed zero.
- \* Due to the limitation of the ISCST model application, for calculations a 25km radius domain from the point source at the centre, the model was executed for the following cases independently: 1) DW & DE, 2) SUB and 3) ZS.
- \* SH uses natural gas for electric power generation which does not contain any sulphur compounds (H<sub>2</sub>S or mercaptans) and it was decided to exclude it from the present study.
- \* The remaining four power stations were assumed to rely entirely on Heavy Fuel Oil (HFO). This assumption though seems pragmatic, had to be made to simplify the modelling part of the project.

The annual total energy generated from each station was calculated, then the amount of HFO required to produce this amount of energy under existing operating conditions was found. S% in the fuel was then varied to cover 1, 2, 3 and 4S% (assuming no change in calorific value with S% variation).

- \* No flue gas desulphurisation units were used in the stations.
- \* The effect of building downwash was not considered.
- \* No plume depletion, whether wet or dry, was used.
- \* The electrical energy was assumed to be generated from steam turbine units only.

To assess the effect of the load cycle on SO<sub>2</sub> ground level concentration, the model was run for the following cases: 1) Peak load (No load cycle), 2) Seasonal cycle only and 3) Hourly and seasonal cycle. For each case, different scenarios (1, 2, 3 and 4S%) in fuel were tested.

**Variations in emission rates:** ISCST3 has several options to input the variable emission rates. For this study, the hour and season (96 values) option was chosen and the cycle was applied to all sources. The actual emission rate for each source was fed in the source constant emissions data and multiplicative scaling factors in the variable emissions data. The data obtained from NCC-MOE was used to calculate the scaling factors resulting in four curves for winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November) as illustrated in (Fig. 3).

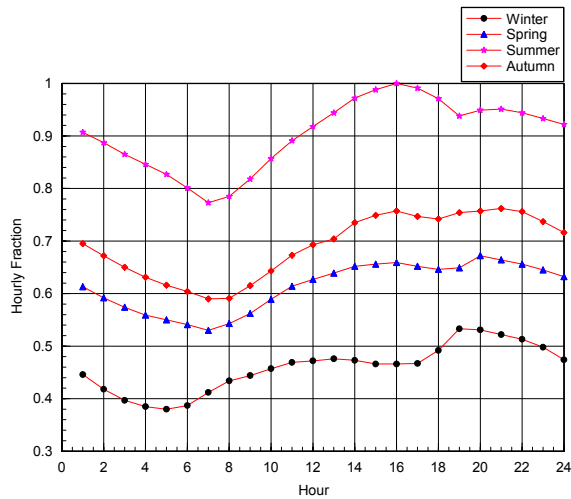


Fig. 3: Hourly fractions for different seasons as used in the numerical model

**RESULTS AND DISCUSSION**

The crucial emission rate used here corresponds to the maximum fuel consumption for the existing peak load at 16 hour during summer. This emission rate is assumed constant with time and is used for the entire year for a special case, *i.e.* Case A, to investigate the influence of meteorological parameters. In Case B, the load was assumed independent of the hour of the day but it varied with season, hence the term “seasonal load cycle”. The seasonal load cycle multiplicative factors were: winter season (51%), spring season (68%), summer season (100%) and autumn season (77%). For Case C, the emission rates varied both hourly and seasonally following the hourly fractions curves shown in Fig. 3.

In this communication, due to space limitations, the hourly and annual SO<sub>2</sub> concentrations will not be discussed in details and reference to it will only be made when necessary. The daily isopleths plots will present only the regions of SO<sub>2</sub> concentrations above KEPA residential threshold values (Table 2).

**Case A: Peak load (no cycle):** It is interesting to note that the high hourly SO<sub>2</sub> concentrations occur between 11-14 hours during May 2000, August 2000, August 2001 and June and August 2003. These high concentrations at these times are solely due to the weather conditions as the emission rates were kept constant throughout these runs. The computed yearly SO<sub>2</sub> concentrations resulting from DE and DW, SUB and ZS were systematically below KEPA Annual

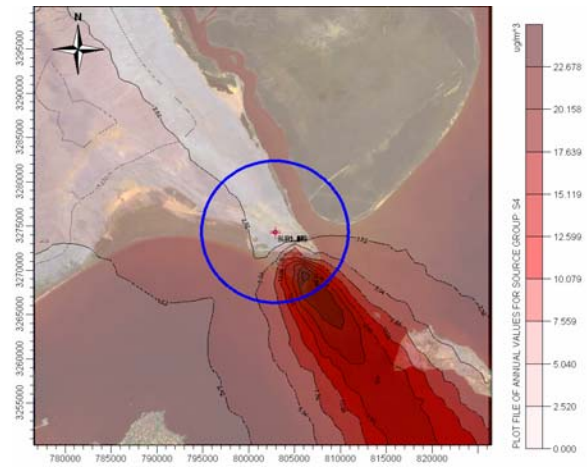


Fig. 4: Annual SO<sub>2</sub> concentrations for SUB at 4S% with  $r_A = 0\%$  – CASE A

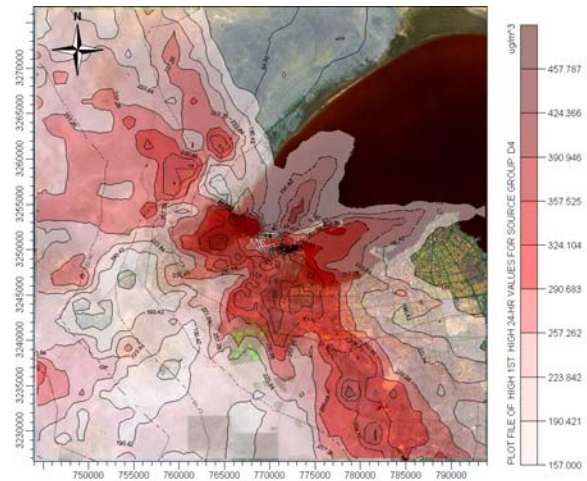


Fig. 5: Daily SO<sub>2</sub> concentrations for DW DE at 4S% with  $r_A = 75.83\%$  – CASE A

Standard (KEPAAS) value of 80µg<sup>-3</sup> even for 4S%, hence, no violation of KEPA annual standards. The effect of the prevailing north-western wind direction (Fig. 2) is indisputable in the annual concentrations isopleths and the plume is perfectly aligned with the wind direction, (Fig. 4.) The maximum annual concentrations are listed in Table 3.

**Doha east and doha west power stations:** The stacks of DE and DW power stations are about 900m apart. The cumulative effect of the emissions released by the two stations is unambiguous in the daily and annual concentrations. The calculated daily SO<sub>2</sub> concentrations comply with KEPA Daily Standard (KEPADS) value of 157µg<sup>-3</sup> for 1S% but not for 2, 3 and 4S%.



Table 3: The violation times and maximum concentrations - No Cycle case  
Doha West-Doha East Power Station

| S%                                       | Max. Conc. ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
|--|-------------------------------------|----------------|---------|--|
| <b>Doha West-Doha East Power Station</b> |                                     |                |         |  |
| Daily                                    |                                     |                |         |  |
| 1.00                                     | 114                                 | N              | 0.00    | N/A  |
| 2.00                                     | 229                                 | Y              | 7.38    | 29 March, 4 May, 10 July & 9 Aug 03 / 16 May, 4 Jun & 18 Jun 00                                    |
| 3.00                                     | 343                                 | Y              | 51.67   | 30 March, 4 May, 10 July & 9 Aug 03 / 16 May, 4 Jun & 18 Jun 00                                    |
| 4.00                                     | 458                                 | Y              | 75.83   | 31 March, 4 May, 10 July & 9 Aug 03 / 16 May, 4 Jun & 18 Jun 00                                    |
| Annual                                   |                                     |                |         |  |
| 1.00                                     | 16                                  | N              | 0.00    | N/A  |
| 2.00                                     | 33                                  | N              | 0.00    | N/A  |
| 3.00                                     | 49                                  | N              | 0.00    | N/A  |
| 4.00                                     | 66                                  | N              | 0.00    | N/A  |
| <b>Subiya Power Station</b>              |                                     |                |         |  |
| S%                                       | Max Conc ( $\mu\text{g m}^{-3}$ )   | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                                    |                                     |                |         |  |
| 1.00                                     | 67                                  | N              | 0.00    | N/A  |
| 2.00                                     | 133                                 | N              | 0.00    | N/A  |
| 3.00                                     | 200                                 | N              | 0.00    | N/A  |
| 4.00                                     | 267                                 | Y              | 0.40    | 3 Jun & 28 Jul 99 / 5 Apr, 16 May & 18 Jun 00 / 2 & 12 Aug, 18 Sep 01 / 29 March, 1 Jul & 9 Aug 03 |
| Annual                                   |                                     |                |         |  |
| 1.00                                     | 6                                   | N              | 0.00    | N/A  |
| 2.00                                     | 11                                  | N              | 0.00    | N/A  |
| 3.00                                     | 17                                  | N              | 0.00    | N/A  |
| 4.00                                     | 23                                  | N              | 0.00    | N/A  |
| <b>Zour South Power Station</b>          |                                     |                |         |  |
| S%                                       | Max Conc ( $\mu\text{g m}^{-3}$ )   | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                                    |                                     |                |         |  |
| 1.00                                     | 145                                 | N              | 0.00    | N/A  |
| 2.00                                     | 291                                 | Y              | 0.14    | 4 & 18 Jun 00 / 9 & 13 Aug 03 / 9 Jun 03   |
| 3.00                                     | 436                                 | Y              | 4.35    | 5 May, 4 & 18 Jun & 14 Sept 00 / 9 & 13 Aug 03 & 9 Jun 03  |
| 4.00                                     | 581                                 | Y              | 15.44   | 5 May, 4 & 18 Jun & 14 Sept 00 / 9 & 13 Aug 03 & 9 Jun 03  |
| Annual                                   |                                     |                |         |  |
| 1.00                                     | 10                                  | N              | 0.00    | N/A  |
| 2.00                                     | 20                                  | N              | 0.00    | N/A  |
| 3.00                                     | 31                                  | N              | 0.00    | N/A  |
| 4.00                                     | 41                                  | N              | 0.00    | N/A  |

For 2, 3 and 4S%. The ratio of the area affected by the exceedences to the calculation-domain area

$$\left( r_A = \frac{A_{Exceedence}}{A_{Calculation Domain}} \times 100\% \right) \text{ was } 7.38, 51.67 \text{ and } 75.83\% \text{ respectively.}$$

The exceedences are listed in Table 3. The maximum daily concentration occurs at 4.1km from the stations to the north-western direction (angle = 57.6°). The sign convention is the normal one, i.e. North = 0° with CCW rotation. Figure 5 shows the daily concentration isopleths for 4S%.

**Subiya Power Station:** There is no violation of KEPADS at 1 & 2S%. For 3S%, the calculated daily SO<sub>2</sub> concentration exceeded 157 $\mu\text{g m}^{-3}$  but only once a year, hence there is no violation of KEPADS for 3S%. For 4S%, KEPADS is violated not just only during summer but also during spring season, with the highest daily concentration attained being 267 $\mu\text{g m}^{-3}$ . As Fig. 6

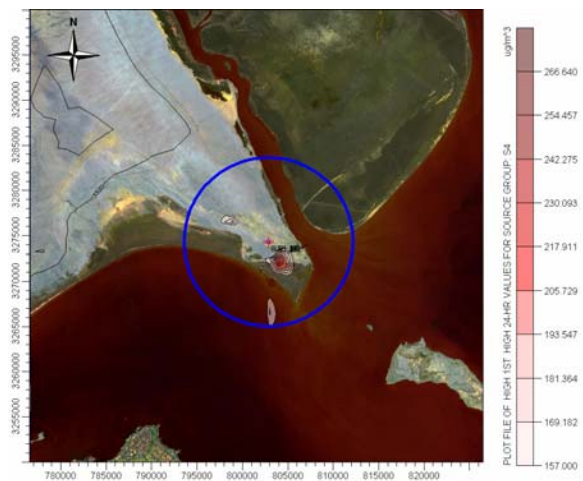


Fig. 6: Daily SO<sub>2</sub> concentrations for SUB at 4S% with  $r_A = 0.40\%$  – CASE A

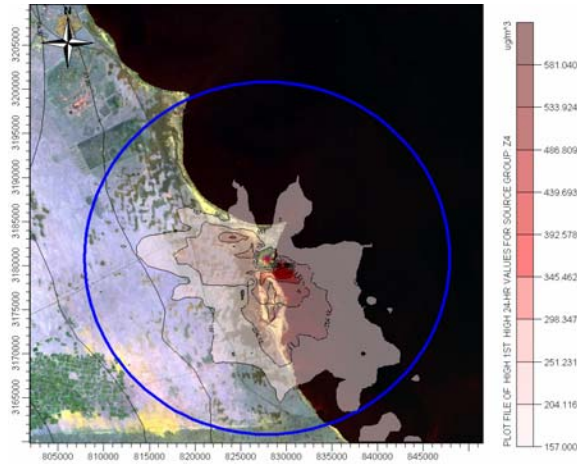


Fig. 7: Daily SO<sub>2</sub> concentrations for ZS at 4S% with  $r_A = 15.44\%$  – CASE A

shows, at 4S% the region affected by daily SO<sub>2</sub> concentrations above KEPAAS is very small, *i.e.*  $r_A = 0.40\%$  and it is enclosed within a circle of 9.3km radius from the centroid of SUB. The point of highest concentration is at 1.75km from the station and the effect of the prevailing north-western wind direction onsets to be apparent as this point is at 210° from the station (southeast). The maximum daily concentrations with violation times are listed in Table 3.

**Zour South Power Station:** For 1S%, the computed daily concentrations show no violation of KEPAAS. At 2S%, KEPAAS is violated and the maximum daily concentration is 290 $\mu\text{g}\text{m}^{-3}$  at 1.7km from the station at an angle of 225° (southeast). At 4S%, the region affected by daily SO<sub>2</sub> concentrations higher than KEPAAS can be enclosed by a circle of 20km radius as can be seen in (Fig. 7)  $r_A$  changes from 0.14% at 2S% to 15.44% at 4S%.

**Case B: Seasonal cycle:** For this case, the high hourly SO<sub>2</sub> concentrations continued to come about between 11-14 hours in the summers of 1999, 2000 and 2001. These high concentrations are not a result of increased emissions at these times as no hourly cycle was used in the calculations. Unfavourable meteorological conditions in the form of low wind speed and eastern wind direction are expected to be the reason behind these violations. This argument is supported by the findings of Alkama and Ourtirane<sup>[17]</sup>. The fact that the high hourly concentrations take place in some years but not the others strengthens the argument that the reason

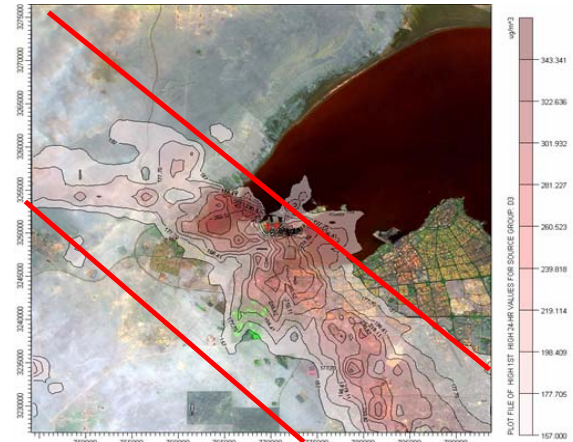


Fig. 8: Daily SO<sub>2</sub> concentration due to DW & DE at 3S% with  $r_A = 27.59\%$  – CASE B

behind these violations is related to the meteorological conditions rather than the variation in hourly load.

The computed yearly SO<sub>2</sub> concentrations due to DE and DW, SUB and ZS are less than KEPAAS for the range of S% under consideration and no violations of KEPAAS have been observed. The highest yearly average concentration for 4S% is approximately 21% less than the corresponding value for Case A and 8 to 12% higher than the corresponding value for Case C. The maximum annual concentrations are listed in Table 4.

**Doha East and Doha West power stations:** For 1S%, the computed maximum daily SO<sub>2</sub> concentration is less than KEPAAS. However, KEPAAS is violated during summer at 2, 3 and 4S% due to the increased generation of electrical energy to cope with the higher demands during summer. Urban areas are affected by high daily SO<sub>2</sub> concentrations even for 2S%, for which  $r_A = 4.40\%$ . For 3S%, the region affected by high SO<sub>2</sub> concentration grows, *i.e.*  $r_A = 27.59\%$ , to form a 5-10km wide segment aligned with the prevailing wind direction in Kuwait, (Fig. 8). This region continually grows for 4S% affecting more urban areas and placing most of the high concentration points downwind of the stations (south-east). At 4S%,  $r_A = 54.33\%$  and the calculated maximum daily SO<sub>2</sub> concentration was 458 $\mu\text{g}\text{m}^{-3}$ , which is about 3 times the KEPAAS and nearly 6% greater than the corresponding value for Case C.

**Subiya power station:** For 1-3S%, there is no violation of KEPAAS. At 4S%, KEPAAS is violated with a computed maximum daily concentration of 267 $\mu\text{g}\text{m}^{-3}$

Table 4: The violation times and maximum concentrations – Seasonal Cycle

| Doha West-Doha East Power Station |                                   |                |         |  |
|-----------------------------------|-----------------------------------|----------------|---------|--|
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 114                               | N              | 0.00    | N/A  |
| 2.00                              | 229                               | Y              | 4.40    | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01 / 9 Jul 02 / 30 Aug 02 / 10 Jul 03 / 9 Aug 03 |
| 3.00                              | 343                               | Y              | 27.59   | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01 / 9 Jul 02 / 30 Aug                           |
| 4.00                              | 458                               | Y              | 54.33   | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01 / 9 Jul 02 / 30 Aug                           |
| Annual                            |                                   |                |         |  |
| 1.00                              | 13                                | N              | 0.00    | N/A  |
| 2.00                              | 27                                | N              | 0.00    | N/A  |
| 3.00                              | 40                                | N              | 0.00    | N/A  |
| 4.00                              | 54                                | N              | 0.00    | N/A  |
| Subiya Power Station              |                                   |                |         |  |
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 67                                | N              | 0.00    | N/A  |
| 2.00                              | 133                               | N              | 0.00    | N/A  |
| 3.00                              | 200                               | N              | 0.00    | N/A  |
| 4.00                              | 267                               | Y              | 0.27    | 3 Jun , 11 & 28 Jul 99 / 9 Aug & 1 Jul 03  |
| Annual                            |                                   |                |         |  |
| 1.00                              | 5                                 | N              | 0.00    | N/A  |
| 2.00                              | 9                                 | N              | 0.00    | N/A  |
| 3.00                              | 14                                | N              | 0.00    | N/A  |
| 4.00                              | 19                                | N              | 0.00    | N/A  |
| Zour South Power Station          |                                   |                |         |  |
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 145                               | N              | 0.00    | N/ A   |
| 2.00                              | 291                               | Y              | 3.33    | 4 & 18 Jun 00/ 9 & 13 Aug 03/ 9 Jun 03   |
| 3.00                              | 436                               | Y              | 0.00    | 4 & 18 Jun 00/ 9 & 13 Aug 03/ 9 Jun 03   |
| 4.00                              | 581                               | Y              | 10.44   | 4 & 18 Jun 00/ 9 & 13 Aug 03/ 9 Jun 03   |
| Annual                            |                                   |                |         |  |
| 1.00                              | 8                                 | N              | 0.00    | N/A  |
| 2.00                              | 17                                | N              | 0.00    | N/A  |
| 3.00                              | 25                                | N              | 0.00    | N/A  |
| 4.00                              | 34                                | N              | 0.00    | N/A  |

(9% greater than the corresponding value for Case C) at 1.75km from the station to the south-east and  $r_A=0.27\%$ . The locations for the 50 highest daily concentrations are within a circle of 8.8km radius around SUB. The maximum daily concentrations are listed in Table 4.

**Zour South power station:** KEPADS is violated at 2, 3 and 4S%. The violation takes place during the summers (due to increased fuel consumption to meet the higher demand on electricity) of 2000 and 2003 further supporting the argument used for the cases of SUB, DW and DE stations. For 2S%,  $r_A=0.12\%$  and it grows to reach  $r_A=3.33\%$  for 3S%. The highest daily  $\text{SO}_2$  concentration obtained for 4S% was  $581\mu\text{g m}^{-3}$  and

$r_A=10.44\%$ . Fig. 9 shows that the region suffering from daily  $\text{SO}_2$  concentrations above KEPADS for 4S% can be enclosed by a circle of 20km radius.

**Case C: Variable load:** For this case, the highest hourly  $\text{SO}_2$  concentrations continue to transpire between 11-14 hours during the summer season. On the outlook, the time of violations can be linked to the shape of the hourly load curve shown in (Fig. 3), *i.e.* the power generation load after 11 hours is always more than 90% with its peak at 16 hours for the summer season. However, this argument is weakened by the fact that these high concentrations do not occur in all years (which have the same load cycle as the other years when high concentrations occur) leaving the meteorological conditions to play the major role is the



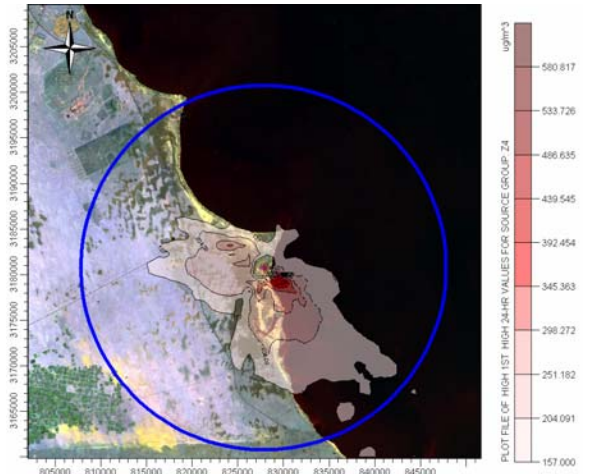


Fig. 9: Daily SO<sub>2</sub> concentration due to ZS at 4S% with  $r_A=10.44\%$  – CASE B

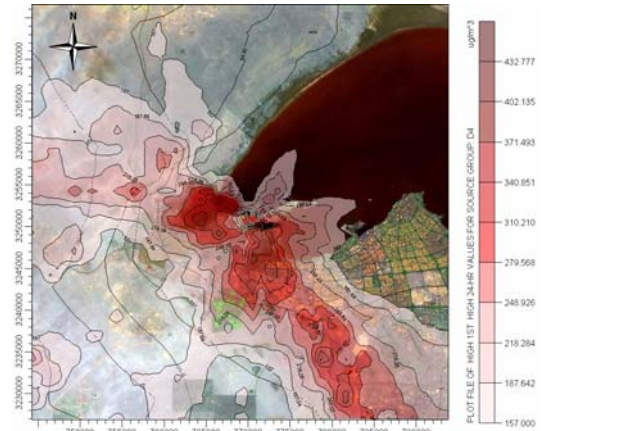


Fig. 10: Annual SO<sub>2</sub> concentration due to DW DE at 4S% with  $r_A=45.40\%$  – CASE C

computed ground level concentrations.

The yearly SO<sub>2</sub> concentrations resulting from DE and DW, SUB and ZS are less than KEPAAS for all S% considered, hence, no violations of KEPAAS are noticed. The plume remains aligned with the prevailing wind direction and all the high concentration points are to the south east of the stations, highlighting the advantage of the locations of SUB and ZS. The maximum annual concentrations are listed in Table 5.

**Doha East and Doha West power stations:** The computed daily SO<sub>2</sub> concentrations resulting from 1S% are less than KEPADS. For 2, 3 and 4S%, the KEPADS is violated every summer season when the coefficients of the power generation seasonal/hourly cycle is the highest and the appropriate meteorological conditions are met. At 2S%, the region affected by high daily SO<sub>2</sub> concentrations is relatively small,  $r_A=2.14\%$  and no urban area is affected. As can be (Fig. 10), the regions affected by SO<sub>2</sub> concentration violating the KEPADS increase outreaching urban areas for 3 and 4S% for which  $r_A=21.63\%$  and  $45.40\%$  respectively. The highest daily SO<sub>2</sub> concentration obtained for 4S% was  $432\mu\text{g}\text{m}^{-3}$  (nearly 3 times the KEPADS) at 4.1km distance and angle =  $58^\circ$  (north west of the stations).

**Subiya Power Station:** The daily SO<sub>2</sub> concentrations for 1-2S% are less than KEPADS. For 3S%, the KEPADS is transcended at three locations, but only once a year (during June), hence no violation of KEPA standards for 3S% is observed. For 4S%, KEPADS is violated with the highest daily concentration attained

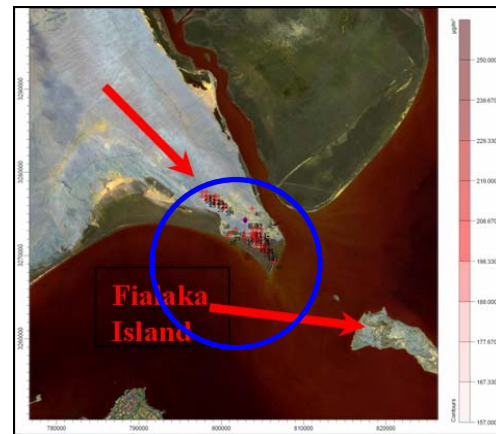


Fig. 11: Daily SO<sub>2</sub> concentration due to SUB at 4S% with  $r_A=0.19\%$  – CASE C

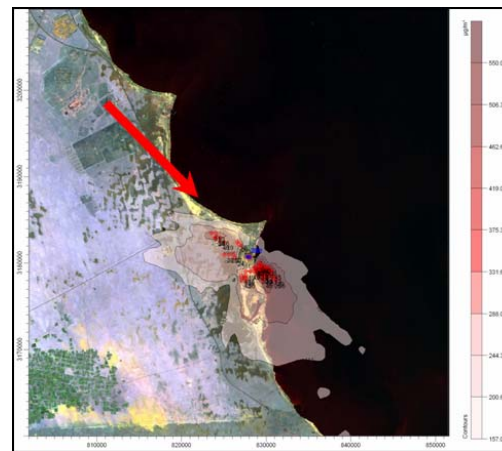


Fig. 12: Daily SO<sub>2</sub> concentration due to ZS at 4S% with  $r_A=8.18\%$  – CASE C



Table 5: The violation times and maximum concentrations – Hourly and Seasonal Cycle

| Doha West-Doha East Power Station |                                   |                |         |  |
|-----------------------------------|-----------------------------------|----------------|---------|--|
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 108                               | N              | 0.00    | N/A  |
| 2.00                              | 216                               | Y              | 2.14    | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01/ 9<br>Jul 02 / 30 Aug 02 / 10 Jul 03/ 9 & 20 Aug 03 |
| 3.00                              | 325                               | Y              | 21.63   | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01/ 9<br>Jul 02 / 30 Aug 02 / 10 Jul 03/ 9 & 20 Aug 03 |
| 4.00                              | 433                               | Y              | 45.40   | 12 Jun 99 / 17 Aug 99 / 4 & 18 Jun 00 / 12 & 28 Aug 01/ 9<br>Jul 02 / 30 Aug 02 / 10 Jul 03/ 9 & 20 Aug 03 |
| Annual                            |                                   |                |         |  |
| 1.00                              | 12                                | N              | 0.00    | N/A  |
| 2.00                              | 25                                | N              | 0.00    | N/A  |
| 3.00                              | 37                                | N              | 0.00    | N/A  |
| 4.00                              | 50                                | N              | 0.00    | N/A  |
| Subiya Power Station              |                                   |                |         |  |
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 62                                | N              | 0.00    | N/A  |
| 2.00                              | 123                               | Y              | 0.00    | N/A  |
| 3.00                              | 185                               | Y              | 0.00    | N/A  |
| 4.00                              | 246                               | Y              | 0.19    | 3 Jun & 28 Jul 99 / 9 Aug & 1 Jul 03   |
| Annual                            |                                   |                |         |  |
| 1.00                              | 4                                 | N              | 0.00    | N/A  |
| 2.00                              | 9                                 | N              | 0.00    | N/A  |
| 3.00                              | 13                                | N              | 0.00    | N/A  |
| 4.00                              | 17                                | N              | 0.00    | N/A  |
| Zour South Power Station          |                                   |                |         |  |
| S%                                | Max Conc ( $\mu\text{g m}^{-3}$ ) | KEPA Violation | $r_A\%$ | Violation Time   |
| Daily                             |                                   |                |         |  |
| 1.00                              | 135                               | N              | 0.00    | N/A  |
| 2.00                              | 270                               | Y              | 0.09    | 4 & 18 Jun 00 / 9 & 13 Aug / 9 Jun 03  |
| 3.00                              | 404                               | Y              | 2.52    | 4 & 18 Jun 00 / 9 & 13 Aug / 9 Jun 03  |
| 4.00                              | 539                               | Y              | 8.18    | 4 & 18 Jun 00 / 9 & 13 Aug / 9 Jun 03  |
| Annual                            |                                   |                |         |  |
| 1.00                              | 7                                 | N              | 0.00    | N/A  |
| 2.00                              | 15                                | N              | 0.00    | N/A  |
| 3.00                              | 23                                | N              | 0.00    | N/A  |
| 4.00                              | 31                                | N              | 0.00    | N/A  |

being  $246\mu\text{g m}^{-3}$  at 1.75km from the station to the south-eastern direction. The region affected by high daily  $\text{SO}_2$  concentrations is unnoticeable, *i.e.*  $r_A=0.19\%$  and it can be enclosed by a circle of 6.24km radius, (Fig. 11). The north-western and south-eastern winds force the locations of high concentrations to scatter around a straight line stretching from northwest to southeast.

For ZS, the KEPADS is violated for 2, 3 and 4S% cases. Similar to SUB, DW and DE stations, the highest daily  $\text{SO}_2$  concentrations transpire during summer. The highest daily  $\text{SO}_2$  concentration obtained for 4S% was  $539\mu\text{g m}^{-3}$ . At 2S%, the region affected by high daily  $\text{SO}_2$  concentrations is small, *i.e.*  $r_A=0.09\%$  and no urban area is affected. The regions influenced by  $\text{SO}_2$  concentration above KEPADS grow in both north-western and south-eastern directions for 3 and 4S% as

can be (Fig. 12). The 50 highest concentrations take place within a circle of 4.75km radius.

## CONCLUSION

The maximum computed hourly and daily ground level concentrations are the same for the no cycle and seasonal cycle cases and they occur during the summer season. For these two cases, the emission rate is consistent for the entire year for the no cycle case and is equivalent to the emission rate for the summer period for the seasonal cycle case resulting in identical maximum ground level concentration at a specific location and time for the prevailing meteorological conditions. For hourly and seasonal combined cycle there is 9.2% and 7.3% average reduction in computed values of hourly and daily ground level concentrations

respectively (compared to the no cycle and seasonal cycle cases) due to continuous hourly variation in emission rates throughout the year. The annual computed ground level concentrations are different for all three cycles depicting the annual variation in emission rates from no cycle to seasonal and combined hourly and seasonal cycle. There has been 21.1% reduction due to season seasonal cycle and 31.4% reduction for the most realistic operation conditions for combined hourly and seasonal cycle.

The ratio of the area affected by the exceedences to the calculation-domain area, *i.e.*  $r_A$ , is affected by two factors: S% and the emission cycle as illustrated in Figs. 13 and 14.  $r_A$  increases with S% until  $r_A$  reaches 100% when further increase in S% results in increased ground level concentrations only.  $r_A$  increases gradually as we move from the combined hourly and seasonal cycle to the seasonal cycle and finally to the no cycle case.

Other findings are:

- \* KEPADS is maintained if all the power stations use HFO with 1S% or less.
- \* KEPAAS is maintained at all S% simulated.
- \* All KEPA violations occur between 11-14 hours during summer season when the demand on electrical energy is high and the appropriate meteorological conditions are met.
- \* The effect of the north-western prevailing wind direction onsets to appear on daily results and is most profound on annual results.
- \* The concentrations obtained for the combined hourly and seasonal cycle were in general less than those of the constant and the seasonal cycle cases.
- \* The location of SUB station is ideal for extension or even building new power stations as even for 4S% under variable load conditions, the high hourly SO<sub>2</sub> concentrations do not affect urban areas. This continues to be valid as long as Failaka Island remains uninhibited.

For the daily and annual SO<sub>2</sub> concentrations, enhanced dispersion has the following effects: a) increasing the region of influence of high SO<sub>2</sub> concentrations whilst causing the 50 higher SO<sub>2</sub> concentrations to be reached closer to the source, b) increasing the maximum daily and annual SO<sub>2</sub> concentrations.

The locations of the existing power stations have many benefits, e.g. a) proximity to sea water which is used for desalination as well as for steam turbines and cooling purposes and b) due to the prevailing north-western wind direction the high pollutant

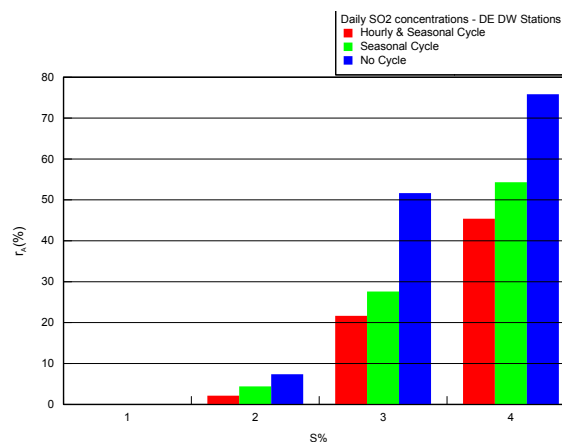


Fig. 13: Variation in the daily  $r_A$  due to the change in S% and the emission Cycle for DE DW stations

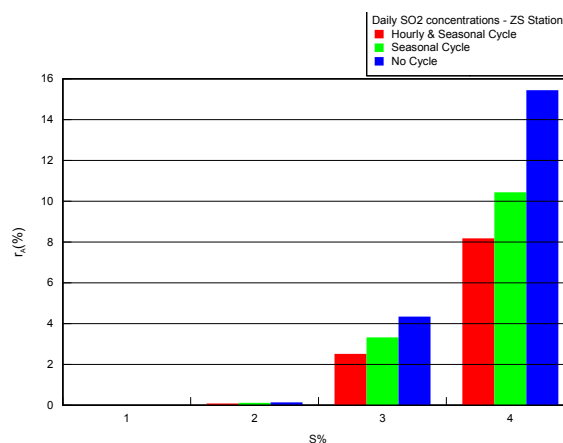


Fig. 14: Variation in the daily  $r_A$  due to the change in S% and the emission Cycle for ZS station

concentrations for ZS and SUB power stations occur offshore. However, the increased airborne pollutant levels above the Arabian Gulf is expected to have adverse effect on the marine life. Until the time has come to completely switch to cleaner fuels and renewable sources of energy the best solutions seems to improve the efficiency of power generation systems through: a) Combined-cycle systems, b) Combined heat and power production, c) System rehabilitation and boiler tuning and d) Electric power system interconnections (Hamzeh<sup>[1]</sup>).

When using the combined hourly and seasonal cycle in the calculations, *i.e.* Case C, the violations of KEPA standards at 11-14 hours during the summer can be readily attributed to the higher demand on electricity at those times. This is plausible as the majority of employed people reach their houses after work at this

time and the use of electrical utilities peaks. Hence, researchers tend to believe this surge in electricity usage is the main reason for the KEPA violations. However, when the model is run at constant load (Case A) and at seasonal load cycle with no hourly variation (Case B), the above mentioned argument is weakened. As the presented results have shown, the violations during 11-14 hours in *some* summer seasons continue directing attention to the meteorological conditions and their significant influence on dispersion of emissions. The argument is reinforced when one remembers that the violations took place during the above-mentioned times in the summers of 1999, 2000 and 2001 but not during 2002 and 2003 although the emissions were identical for all years. This is conceivable when considering that serious pollution episodes in cities aren't directly caused by sudden increase in pollutant emissions but result from unfavourable meteorological conditions, Alkama and Ourtirane<sup>[17]</sup>. According to them, the meteorological parameters that provoke pollutants increase are: temperature, relative humidity and wind.

The Careful examination of the meteorological data for times of violations reveals that the stability category for the violations times ranges between moderately unstable (stability category A) to extremely unstable (stability category B) category which is characterised by strong thermal instability and bright sun light.

At present we are trying to correlate the hourly, daily and annual results to meteorological data and this is expected to be the subject of future communication.

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