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MODEL PREDICTION OF SULPHUR DEPOSITION ARISING FROM THE SO_2 EMISSIONS AT KALGOORLIE

Report to Kalgoorlie Consolidated
Gold Mines and WMC Kalgoorlie
Nickel Smelter

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

A modelling study has been carried to estimate the long-term average ground level concentrations (glc) of SO_2 and the extent of dry and wet sulphur species deposition resulting from the emissions from gold roasting and nickel smelting operations associated with Kalgoorlie. The impacts of the modelled glc and deposition on crops or vegetation are briefly assessed.

Modelling procedures

SO_2 glc

Two simple models of plume behaviour were employed, one for modelling glc etc out to 100 km from the sources, the second dealing with long-range transport for up to 1000 km.

(a) Short-range model

The first model was a Gaussian puff model, whereby a 1 h long puff from each of the sources, (the Gidji and Oroya roasters and the Kalgoorlie nickel smelter (KNS)) was tracked out to 100 km according to the 1 h average windspeed and direction measured at Kalgoorlie at the time of emission. The crosswind concentration profile was assumed to be Gaussian. The plume was allowed to spread horizontally and vertically, at a rate consistent with experimental data on plume dispersion for the meteorological conditions. SO_2 glc were calculated at sites specified by a grid of 2 km resolution. When the plumes from the three sources overlapped at a given location, the individual glc were summed. Then another 1 h puff from each of the sources was tracked with an updated windspeed and direction. Variation in emission strengths was taken into account.

These calculations were performed for daytime periods only, as during the night, it was assumed that the plumes did not mix to the ground. The results from running the model every day for a year using emission and meteorological data for the year from August 1990 to July 1991 have been summed to produce 3 month and annual averages of glc.

(b) Long-range model

Plume trajectories were calculated from 6 hourly wind speed and direction data derived from pilot balloons/radiosondes released at Geraldton, Perth, Kalgoorlie, Esperance and Forrest. The plume was deemed to have moved for 6 h with the speed and direction measured at the nearest balloon site starting with Kalgoorlie. The emissions were treated as a single plume and were tracked for 1000 km or 48 h whichever came first. The plume was then considered to have moved uniformly in a straight line between Kalgoorlie and the end point of the 1000 km (or 48 h) trajectory. These trajectories, with a resolution of 6 h, were determined for the entire year. The plume centreline was superimposed on these trajectories and allowed to spread laterally according to experimental data on long-range plume dispersion. SO_2 glc were calculated on a 20 km grid.

Dry deposition

The extent to which SO_2 was absorbed by soil and vegetation, a process known as dry deposition, was calculated using experimentally determined rates of dry deposition. As the process is linearly proportional to SO_2 glc, the calculations are a simple adjunct to the model for glc.

Wet deposition

The complexity of the meteorology associated with rain and the physics and chemistry of atmospheric SO_2/ water systems makes modelling wet depostional processess highly uncertain. The approach taken here has been to use selected rainfall statistics for an area bounded by Geraldton, Perth, Albany, Esperance, and Forrest to determine how many days in the year it rained at various locations. If the plume trajectory on a rain day was even crudely in the vicinity of that site, then wet deposition was deemed to have occurred. This is a very conservative approach.

The extent of wet deposition was estimated by using the fraction of the annual rainfall when the SO_2 plume was in the vicinity of the site and assuming the rainfall had pH = 5 (due to bisulphite ion) and a temperature of 15°C. The amount of bisulphite was calculated assuming the rain to be in equilibrium with the modelled SO_2 glc at that location.

Results

SO_2 glc

The results of the short-range modelling using meteorological and emissions data for the year 01/08/90 to 31/07/91 show that the annual average isopleths of SO_2 glc for a concentration of 5 $\mu g/m^3$ did not extend beyond 50 km from Kalgoorlie, whilst the isopleths representing 20 $\mu g/m^3$ and higher for Gidji and KNS were sufficiently close to the respective sources that they did not overlap. The 20 $\mu g/m^3$ contour extended about 8 km from Gidji and 12 km from KNS. The calculated seasonal (3 month) isopleths extended a little further out from the sources, those for winter showing the effect of shutdown of the Gidji roaster on glc around Kalgoorlie. The emissions data for the year 1990/1991 resulted in an annual average SO_2 emission rate of 3.6 kgs^{-1} and 7.6 kgs^{-1} for the Gidji roaster and the nickel smelters respectively.

The long-range model calculations for the same period indicate that the annual average isopleths of SO_2 glc for 0.5, 1 and 2 $\mu g/m^3$ did not extend beyond ~650, 300 and 150 km respectively from Kalgoorlie. For the wheat belt which starts about 150 km west of Kalgoorlie, calculated annual averages are in the range 0.5 to 2 $\mu g/m^3$.

Dry deposition

The annual amount of SO_2 absorbed by the soil and vegetation was estimated to be less than 1 kg/ha when more than 650 km from the sources and did not exceed 50 kg/ha until within about 5 km from either Gidji roaster or 8 km from the nickel smelter.

Wet deposition

The annual wet deposition for rain at temperature 15°C, was estimated to range from 0.3 kg SO_2 equivalent/ha at Geraldton to 3 kg/ha at Norseman.

Uncertainties in the calculations

There are numerous sources of uncertainties in this type of modelling. However, over lengthy averaging periods such as a year, we estimate that the modelled annual average glc are accurate to within a factor of ~2. The accuracy of the calculations can be better assessed with the establishment of SO_2 monitors about 50 km away from Kalgoorlie.

The uncertainty in the estimates of dry deposition are likely to be similar to those for annual average SO_2 glc.

The uncertainty in the estimates of wet deposition are larger than the uncertainties for the annual average SO_2 glc. Similarly the extent of wet deposition can be assessed by establishing rainfall chemistry collectors at selected locations within the agricultural region.

Effects on crops and pastures

SO_2 glc

In order to provide a guide to possible effects of SO_2 on crops, particularly cereals, we have surveyed recent published literature on this topic. This indicates that exposure to less than 45 $\mu g/m^3$ over the entire growing season has no significant effect on yield or growth, with most studies finding no effect until levels exceeded 150 $\mu g/m^3$. A seasonal (3 month) exposure level of 45 $\mu g/m^3$ is only found within 15 km of the sources, whilst the 150 $\mu g/m^3$ isopleth lies less than ~5 km away. The annual average concentrations over the wheat belt are modelled to be less than 2 $\mu g/m^3$. Consequently, taking the results of this modelling study, in conjunction with the above data on the effect of SO_2 on wheat, it would appear that SO_2 emitted from the gold roasters and nickel smelter is unlikely to have significant impact on agriculture within the wheat belt. However, further specialist advice should be taken on this matter.

SO_2 dry deposition

Typical application rates of S fertilizer to improved pastures are around 20 to 40 kg SO_2 equivalent/ha/y. (Little S fertilizer is added to cultivated soils, which rely on mineral S being made available through the cultivation process). The annual average depositional

isopleths which enclose this rate of application do not extent further than ~10 and ~15 km from Gidji or the nickel smelter. Thus, in the absence of fertilizer application, excess sulphur is only likely to be encountered close to the sources.

Because of the number and complexity of the processes involved it is clear that the results of the calculations presented in this report can only serve as an approximate guide to potential sulphur deposition. If the modelled deposition rates, taking into account the uncertainties involved, give any reason for concern then the only method of confirming the estimates is by a program of direct measurement, particularly in the areas which might be considered sensitive to sulphur deposition.

ABSTRACT

Calculations of the annual average ground level concentration of SO_2 and dry and wet deposition of sulphur compounds from the KCGM and KNS SO_2 sources at Kalgoorlie have been carried out for the period August 1990 to July 1991. SO_2 emissions, averaged over the entire year, were 3.6 kg s^{-1} and 7.6 kg s^{-1} for the Gidji roaster and the nickel smelter respectively.

Two models were employed to predict ground level concentrations of SO_2. These were a) a gaussian plume model for distances up to ~100 km from the sources and b) a long range trajectory model for distances up to 1000 km from the sources.

The gaussian model used dispersion coefficients and plume rise formulae developed by the authors for a number of sites across Australia, including Kalgoorlie, during convective atmospheric conditions.

The long range trajectory analysis used the 6 hourly pilot balloon data available from the Bureau of Meteorology for the 12 month period under study. Trajectories were started from Kalgoorlie every six hours and a six hour puff tracked until it came under the influence of another wind regime defined by the pilot balloon site closest to the trajectory end points. Wind data from Perth, Geraldton, Kalgoorlie, Esperance and Forrest were used until the endpoint of the puff was greater than 1000 km from Kalgoorlie or 48 hrs had elapsed. On 8 occasions were the trajectory endpoints a distance of less than 100 km from Kalgoorlie. On over 80% of occasions the distance was greater than 600 km while on 63% of occasions the distance was greater than 1000 km.

Ground level concentrations of SO_2 were calculated from a simple model using the long range dispersion data of Carras and Williams (1981a).

Annual average glc did not exceed 5 $\mu g\ m^{-3}$ more than 50 km away from Kalgoorlie for the year studied, whilst 20 $\mu g\ m^{-3}$ was not exceeded when more than about 8 km from Gidji or 12 km from KNS. The seasonal (3 months) isopleths extend a little further out.

Dry deposition was estimated using the deposition velocity data measured by Milne et al. (1979) and Williams et al. (1981). A general value of dry deposition velocity, v = 0.3 cm s^{-1} was assumed to be representative of the region under study.

Dry deposition of SO_2 was calculated to be up to ~ 10 kg $ha^{-1}\ yr^{-1}$ within about 20 km of the sources. By 50 km from the sources this had dropped to ~ 5kg $ha^{-1}\ yr^{-1}$.

Estimates of the wet deposition (as SO_2 equivalent) resulted in maximum values of between 1 to 19 kg $ha^{-1}\ hr^{-1}$ depending on proximity to the sources, the amount of annual rainfall and the average ambient temperature experienced by the rainwater. Rainfall sites considered included Mount Magnet, Geraldton, Dalwallina, Perth, Albany, Esperance, Merredin, Wagin, Forrest Menzies, Laverton and Norseman. Further

estimates of the fraction of rain which fell at each site when the SO_2 plume was in the vicinity of each site reduced these ranges to 0.3 to 6 kg ha^{-1} yr^{-1}.

Estimates of the uncertainty associated with the calculation of glc of SO_2 show the predicted annual averages are probably accurate to within a factor of about 2. The dry deposition fluxes calculated are considered to be also accurate to within a factor of ~ 2. The uncertainties associated with the wet deposition calculations are difficult to quantify but are considered to be at least as great as the uncertainty associated with the dry deposition estimates.

A survey of recent literature on the effect of SO_2 on crops, particularly wheat was carried out to provide a guide on the likely effects of the Kalgoolie emissions on the wheat belt. The data suggested that yield of wheat was unlikely to suffer when the average exposure over the growing season was < 45 $\mu g\ m^{-3}$. As annual average glc over the wheat belt were calculated to be in the range 0.5-2 $\mu g\ m^{-3}$, it is considered that SO_2 concentration from Kalgoorlie are unlikely to have significant impact on the wheat belt. However, further specialist advice should be obtained.

Because of the number and complexity of the processes involved it is clear that the results of the calculations presented in this report can only serve as an approximate guide to potential sulphur deposition. If the modelled deposition rates, taking into account the uncertainties involved, give any reason for concern then the only method of confirming the estimates is by a program of direct measurement, particularly in the areas which might be considered sensitive to sulphur deposition.

1. INTRODUCTION

The deposition of acid gases has been the subject of considerable concern in North America and Europe for well over two decades (see e.g. Galloway et al., 1982, MAP3S/RAINE, 1982, Schwartz, 1989 and Langner and Rodhe, 1991). While considerable progress has been made in identifying and quantifying many aspects of the mechanisms responsible for deposition areas remain where further work is required (Hicks 1991).

In Australia studies of wet deposition have been reported for Sydney, the Hunter Valley region of NSW and the Latrobe Valley in Victoria (see Ayers and Gillet 1984, Ayers et al. 1987, Rothwell et al. 1987 and Fitzgerald 1986). In the latter two studies the major sources of acid gases were considered to be the large power stations located in the two valleys.

Kalgoorlie is a centre for significant emissions of SO_2 into the atmosphere. These emissions are due to the gold roaster at Gidji operated by Kalgoorlie Consolidated Gold Mines (KCGM) and the nickel smelter operated by Western Mining Corporation (WMC).

During the first four months of the twelve month period studied the Oroya gold roaster also emitted SO_2 into the atmosphere.

This report contains details and results of modelling procedures developed to estimate the likely dry and wet deposition of sulphur compounds out to distances up to approximately 1000 km from Kalgoorlie.

2. EMISSIONS AND METEOROLOGICAL DATA

2.1 Emissions

Figure 1 shows the relative location of the gold roasters and nickel smelter while Table 1 shows the broad emission details for each source.

The WMC Kalgoorlie Nickel Smelter (KNS) provided detailed data on the daily average feed to the nickel smelter as well times when no emissions occurred. These data were used to produce a data file of 1 hour SO_2 emission rates for the 1990/91 year based on the assumption that 85% of the sulphur in the feed was discharged to the atmosphere.

KCGM provided daily emissions data for the Gidji and Oroya roasters as well as times when no emissions occurred. (NB the Oroya roaster emitted SO_2 for only the first four months of the 12 month period under study). The daily data were used to create data files of 1 hour SO_2 emissions for both roasters.

Use of the 1 hour emission data meant that both the nickel smelter and the gold roasters shutdown periods were explicitly taken into account in the modelling of ground level concentrations.

Table 1 also shows the annual average emission rate of SO_2 calculated from the data provided by KGCM and KNS for the 12 month period August 1990 to July 1991. The annual average emission rates were 3.6 kg s^{-1} and 7.6 kg s^{-1} for the Gidji roasters and the nickel smelter, respectively.

2.2 Meteorological data

Wind speed and direction data were obtained from two sources as follows; a) a 30 m and 60 m anemometer located 500 m east of the KNS stack and b) a 50 m anemometer located on the Cassidy head frame. The data were in the form of 5 minute values of wind speed and direction for the 12 month period 1990/91 provided and were assumed to describe the meteorology in the vicinity of Kalgoorlie. While either data set could have been used to calculate ground level concentrations of SO_2 we chose the KNS set.

To determine longer range trajectories, pilot balloon data were obtained from the Bureau of Meteorology for the period under study. Data from the stations at Perth, Kalgoorlie, Esperance, Geraldton and Forrest were obtained for altitudes from 300 m to 1500 m at six hourly intervals.

2.3 Rainfall data

Rainfall data were obtained from the Bureau of Meteorology for the sites at Mount Magnet, Geraldton, Dalwallinu, Perth, Albany, Esperance, Merredin, Wagin, Kalgoorlie, Forrest, Menzies, Laverton and Norseman. These data contained daily rainfall for each site and for the 12 month period 1990/91.

3. MODELLING PROCEDURES

Two modelling approaches were used. One used gaussian plume modelling to predict ground level concentrations of SO_2 within ~100 km of the sources. The second modelling procedure was developed from the long range plume measurements of Carras and Williams (1981a, 1988) and was used to predict ground level concentrations of SO_2 at distances up to 1000 km from the sources.

3.1 Short range modelling (< 100 km)

Annual and seasonal (3 month) average glc were calculated by applying a Gaussian plume model with due allowance for plume rise and dispersion to each of the sources. A brief description of the procedures employed follows.

3.1.1 Gaussian Plume Modelling

During daylight hours at Kalgoorlie it is highly likely that the plumes from the Gidji roaster and the nickel smelter will be affected by convective conditions. These conditions give rise to maximum ground level concentrations in the vicinity of the sources and represent a 'worst case' for modelling purposes. Gaussian plume models have been

applied to convective conditions previously by Carras and Williams (1981b) and Weil (1985).

For the purposes of the current study it is sufficient to recall some of the major assumptions of gaussian plume models. These are:

1. The fundamental assumption of the gaussian plume model is that the horizontal and vertical crosswind distributions of plume material are distributed according to a gaussian function with standard deviations σ_y and σ_z respectively.

2. For a pollutant being emitted at a height, H, above the ground, the expression for the ground level concentration χ is normally written as:

$$\chi(x,y,o) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\{-1/2\,(y^2/\sigma_y{}^2 + H^2/\sigma_z{}^2)\} \qquad (1)$$

where it is assumed that when the vertical diffusion becomes restricted by the ground the pollutant is reflected back into the atmosphere. In the above equation, u is the wind speed, Q is the rate at which pollutant is emitted and H is the effective height above the ground at which the pollutant is emitted, i.e. the sum of the stack height and the rise due to buoyancy. Also, in the present calculation when $\sigma_z = 0.5 z_i$, where z_i is the height of the mixed layer the vertical distribution of plume material was assumed to be uniform and σ_z held constant for the remainder of the calculation.

In order to make use of the above equation it is necessary that the values of σ_y, σ_z, Q and H be known. The values of χ (ensemble average) calculated according to (1) are for an averaging time appropriate to the chosen values of σ_y, σ_z and u.

3.1.2 Dispersion coefficients, σ_y and σ_z

Values for σ_y and σ_z in the equation 1 are often obtained from curves of the dispersion coefficient versus distance from the stack as a function of atmospheric stability. Versions of these curves have been presented by a number of workers including the widely used schemes of Turner (1970), Smith (1972), Pasquill (1976) and Briggs (1973).

Experimental measurements by Carras and Williams (1983, 1984a,b, 1986) during convective conditions in Australia have shown that the above schemes do not adequately describe the severely convective atmospheric conditions experienced at many locations in Australia. Instead, Carras and Williams (1983, 1984a,b, 1986) have developed values for σ_y and σ_z based on their measurements for a number of sites widespread across Australia. These sites include Mount Isa, Kalgoorlie, the Hunter Valley, Callide and Gladstone. In summary these workers find that during convective conditions the dispersion curves can be represented by equations of the form:

$$\sigma_y = 4.5 t^{2/3} \qquad (2)$$

and

$$\sigma_z = 3.2t^{2/3} \qquad (3)$$

where t is the time taken for the plume to reach a distance x from the source, i.e. $t = x/u$ and the values of σ_y and σ_z are for an averaging time of ~15 min.

3.1.3 Plume rise

The value of the plume rise used in the gaussian plume model has been given by Briggs (1975) for neutral atmospheric conditions. The plume rise ΔH is given by:

$$\Delta H = \left(\frac{3M}{\beta_m^2 u^2} x + \frac{3}{2\beta_b^2} \frac{F}{u^3} x^2\right)^{1/3} \qquad (4)$$

where the first term on the RHS is the rise due to momentum and the second term the rise due to thermal buoyancy where x is the distance downwind, u is the wind speed, β_m and β_b are empirical entrainment rates, M is the plume momentum flux given by $M = w\,V$ where w is the vertical velocity of the gases, V is the volume flowrate of the exhaust gases, F is the buoyancy parameter which is given by:

$$F = (1 - T_a/T_g)\, Vg/\pi$$

where T_a is the ambient air temperature, T_g is the temperature of the exhaust gas and g is the acceleration due to gravity.

For most reasonably buoyant plumes, i.e. $F > 300\ m^4 s^{-3}$ the buoyancy term dominates the above equation and the momentum term can be neglected. For values of $F < 300\ m^4 s^{-3}$ the momentum term is initially significant and its contribution decreases with increased distance from the source.

In the current work the modelling of plume rise has been based on experimental data (Carras and Williams, 1984a). The scatter in field data on plume rise for hot plumes does not allow the contribution of each of the two terms in equation 4 to be clearly distinguished. Consequently the experimental data of Carras and Williams have been interpreted simply on the basis of thermal buoyancy. For the Kalgoorlie plumes where $F < 300\ m^4\ s^{-3}$ the plume rise has been estimated as follows. In previous work Carras and Williams (1981b) interpreted plume rise in terms of the equation:

$$\Delta H = 1.3\, F^{1/3}\, x^{2/3}\, u^{-1} \qquad (5)$$

where the final plume rise was shown to occur after a particular time interval, t_f, the time of final plume rise. The final plume rise time was obtained from experimental data for real plumes where t_f was defined as the time to reach 90% of final rise:

From a study of a number of power station and smelter plumes Carras and Williams deduced the empirical relation

$$t_f = 2.5\ F^{0.6}$$

for t_f in seconds and F ($m^4 s^{-1}$). The above equation was based on data which showed considerable scatter and the value of t_f for a given buoyancy was the average over scattered data. This approach to plume rise termination results in less plume rise than would be calculated by the Briggs (1975) approach. Consequently it represents a conservative modelling approach.

3.2 Long Range Puff Modelling

Carras and Williams (1981a, 1988) have made aircraft based measurements of the long range dispersion of the Mount Isa copper and lead smelter plumes as well as the Kalgoorlie Nickel Smelter plume. The SO_2 from the smelters at Mount Isa was tracked as far as the Western Australian coast, over Broome. At Kalgoorlie the nickel smelter plume was tracked a distance of ~ 315 km from the source. The limiting factor for the plume tracking distance attained at Kalgoorlie was the variability in the daily weather encountered at Kalgoorlie during the period of measurement (~ 2 weeks in July 1981).

Carras and Williams (1981a) used a simple 8 layer model to attempt to describe the measured locations of plume centroids for their data. The details of this procedure are as follows. Pilot balloon data were obtained from the Bureau of Meteorology for sites in the vicinity of the plume path. The pilot balloon data were used to construct data sets containing wind speed and direction at 8 different altitudes between the ground and 2000 m. The data sets for each site, contained data at typically six hour intervals.

Trajectories for each height were allowed to emanate from the source at regular intervals and these 6 hour 'puffs' were tracked for a succession of 6 hourly periods. In the case of the Mount Isa data these trajectories were constrained by the fact that the plume location had been measured accurately at a given time. Consequently the trajectories produced had to be consistent with the known location of the plume. Also when the 'puffs' had moved a significant distance from Mount Isa they were considered to be under the influence of the wind regime of the pilot balloon data from the meteorological site nearest the current position of the trajectory consistent with the measured plume location.

In the case of the Mount Isa and Kalgoorlie data the above procedure was used to calculate the average age of the measured plumes. These data were then used to construct plots of σ_y versus plume travel time for the long range data. Figure 2 reproduces the data from Carras and Williams (1988). For purposes of modelling in the present study we have used

$$\sigma_y = 0.5t \quad \text{for } \sigma_y \text{ in m and t in s.} \tag{6}$$

This line was proposed as a simple line of best fit to the data of Heffter (1964).

In the present study the above method was used to construct trajectories of plume material from Kalgoorlie as follows. Pilot balloon data of wind speed and direction for 6 hourly balloon releases were obtained from the Bureau of Meteorology for the sites at Kalgoorlie, Perth, Esperance, Forrest and Geraldton. The data for an altitude of 900 m were chosen to be representative of behaviour of the mixing layer and hence plume trajectories and data files were constructed for each site with four values per day of wind speed and direction for the entire year July 1990 to June 1991. Not all the data required to form these data files was always available i.e. on some occasions data were not recorded at the 900 m level but at 1200 m or 1500 m or on other occasions no data were recorded for an entire 24 hour period. In such cases the data inserted for the period in question was obtained either from the previous six hour period or the 600 m or 1200 m level. The modification to the data sets introduced by this procedure amounted to ~ 5% at each site.

Trajectories were calculated for every six hours for the entire year. The pilot balloon data from Kalgoorlie were used to start each calculation. After six hours travel at the speed and in the direction indicated by the pilot balloon data the location of the trajectory endpoint was calculated as was the distance from each of the pilot balloon sites. The pilot balloon data for the next six hours travel was chosen from the site nearest to the trajectory end point. The above procedure was continued until the trajectory end point was greater than a distance of 1000 km from Kalgoorlie or a total simulated travel time of 48 hours had elapsed.

The calculated trajectories were used to create a trajectory frequency distribution and average wind speed for each trajectory direction.

Once the direction distribution had been obtained a puff was superimposed over the trajectory with the concentration of SO_2 given by the equation:

$$\chi = Q_a/(W_y z_i u) \qquad (7)$$

where Q_a is the combined SO_2 emission rate of the nickel smelter and gold roasters, W_y the horizontal width of the plume, z_i the depth of the vertical extent of the plume and u the average wind speed for the trajectory direction. The plume width W_y is given by

$$W_y = 4.9\ \sigma_y$$

where σ_y is given by equation 6.

The major assumption involved in equation 7 above is that the plume was uniformly distributed in the horizontal and vertical cross sections. Also the nocturnal behaviour was considered to be similar to the daytime behaviour. Whilst this is probably true for the vertical distribution, measured horizontal profiles show irregular distributions on the second day's travel (Carras and Williams, 1988). However, over the course of a year such irregularities are evened out. In the context of the present calculations the largest uncertainty is probably associated with the trajectory calculations.

The model described above lies between a detailed Norwegian model of long-range transport and a much simpler Harwell model (Derwent et al. 1989). The Norwegian model uses the actual wind speed and direction for the boundary layer updated every 6 hrs and varies the mixing height according to radiosonde data. The Harwell model on the other hand, employs straight line trajectories, fixed mixing height and fixed wind speed. As is noted in Section 4.4, the Norwegian and Harwell models give similar results.

4. RESULTS AND DISCUSSION

4.1 Ground level concentrations of SO_2

The values of σ_y and σ_z described in section 3.1.2 above were based on the experimental data of Carras and Williams (1984a,1986) and are appropriate for an averaging time of about 15 mins. The wind speed and direction data used in the calculations, however, were averaged over 1 hour. Following Gifford (1975) a better value of σ_y and σ_z for 1 hour would be:

$$\sigma\ (60\ \text{min}) = (t_2/t_1)^{1/4}\ \sigma\ (15\ \text{min})$$

where $t_1 = 15$ min and $t_2 = 60$ min i.e.

$$\sigma\ (60\ \text{min}) = \sqrt{2}\ \sigma\ (15\ \text{min})$$

The dispersion curves given by equations 2 and 3 above have been increased by a factor of $\sqrt{2}$ and used in the subsequent calculations.

4.1.1 Gaussian Plume Model

The gaussian plume model described in Section 3.1 was run for the 12 month period August 1990 to July 1991. The one hourly wind speed and direction data were used along with the 1 hourly emissions data to create glc of SO_2 for each hour of the year provided the hour was between 0800 to 1800 hrs. These values were chosen as estimates of the period of the day during which convective conditions occur. An assumption of the gaussian modelling was that non-zero glc only occur for SO_2 emitted during daytime convective conditions. Calculations were carried out on a 2 km resolution grid centred on Kalgoorlie and extending 100 km in each direction and the mixing height was assumed constant at 2000 m.

The one hour calculated values were averaged to form seasonal values as well as an annual average. Figure 3 shows contours of constant SO_2 concentration (isopleths) for the three month period, July 1991 and August and September 1990. Figures 4 to 6 show similar calculations for the other three month periods during the year. Note in Figure 3 the obvious influence of emission controls at Gidji on glc around Kalgoorlie.

Figure 7 shows the calculated annual average SO_2 glc. Contours of constant SO_2 concentration are shown from 5 $\mu g\ m^{-3}$ up to 200 $\mu g\ m^{-3}$. The 5 $\mu g\ m^{-3}$ isopleth is seen to extend up to ~ 50 km from Kalgoorlie. Kalgoorlie itself is seen to lay between the 20

to 5 μg m^{-3} isopleths with the 100 μg m^{-3} isopleth being located within ~ 5 km from each of the two sources.

Comparison of the annual average calculation of SO_2 with the annual averages measured by the KCGM and KNS SO_2 monitoring network are shown in Table 2 for the monitors described. The annual averages from the gaussian model were obtained by interpolation of the values calculated on the 2 km square grid. The SO_2 monitors are located in parts of Kalgoorlie which are essentially within the 5 to 20 μg m^{-3} isopleths predicted by the gaussian model. A comparison of the two sets of numbers shows that they are in broad agreement within a factor of ~ 2. While this is often considered acceptable for modelling annual average concentrations it is clear that the gaussian model underestimates, in broad terms, the annual average glcs. The reasons for this include neglect of fumigation of elevated plumes due to the onset of mixing and the use of a constant mixing height of 2000m.

To assesss the sensitivity of the predicted annual average glc to the value of σ_y, we have run the model using σ_y (60 min) = 3 σ_y (15 min). This had the effect of decreasing the maximum annual average concentration predicted close to the sources. However at distances greater than ~ 10 km from each source no significant change to the calculated glc was observed apart from smoothing of the contours.

4.1.2 Long Range Plume Modelling

For the purposes of the far field modelling, the emissions for the KNS and KCGM sources were considered to emanate from one point source located in central Kalgoorlie.

Trajectory end points and concentrations were calculated on a six hourly basis for the year's pilot balloon data. This was done by using the trajectory endpoints to construct a resultant trajectory frequency distribution for all the six hour trajectories during the year. A total of 1453 trajectories were calculated and the results binned into 5° intervals. The results of this calculation are shown in Table 3. The direction of the trajectory end points from Kalgoorlie and the total elapsed time (up to a maximum of 48 hours) were used to construct the windspeed distribution as a function of wind direction. These data are also shown in Table 3.

On a number of occasions even after 48 hours of travel time the trajectory end points were less than a distance of 1000 km from Kalgoorlie. Table 4 shows the frequency distribution of end point trajectories as a function of total distance from Kalgoorlie. On 8 occasions the trajectory end points were a distance of less than 100 km from Kalgoorlie. On over 80% of occasions the distance was greater than 600 km with 63% of occasions the distance was greater than 1000 km.

Figure 8 summarises results of the far field calculations. The 0.5 μg m^{-3} isopleth predicted by the trajectory calculation is seen to extend ~500 km to the west of Kalgoorlie, the 1 μg m^{-3} isopleth at ~ 250 km from Kalgoorlie and the 5 μg m^{-3} within ~ 50 km from Kalgoorlie. In the region of overlap between the long range trajectory model results and the gaussian plume model the calculations are in broad agreement.

4.2 Dry Deposition of SO_2

The deposition of SO_2 to arid regions in Australia has been measured by Milne et al (1979) and Williams et al (1981). These workers covered small trees, plants and grasses as well as bare soil with a teflon chamber and measured the decay of SO_2 injected into the chamber as a function of time. From the SO_2 decay and assuming a first order process the dry deposition velocity of SO_2 was measured. These authors found that the dry deposition velocity varied typically from ~ 0.1 cm s^{-1} for the region surrounding Mount Isa in winter time, when the area was under severe water stress, to ~ 0.4 cm s^{-1} near Tennant Creek after recent rain.

In the current work we have taken a value of 0.3 cm s^{-1} to be representative of a mix of dry and wet conditions for the region for which the calculations were performed.

The flux of SO_2 deposited to the surface is assumed to be proportional to the SO_2 concentration:

$$J = v\chi$$

where J is the surface flux, χ the concentration of SO_2 and v the constant of proportionality known as the deposition velocity.

Table 5 shows some values of the total SO_2 deposited in one year assuming a deposition velocity of 0.3 cm s^{-1} for various values of annual average SO_2 concentrations. An annual average SO_2 concentration of 1 μg m^{-3} results in ~ 1 kg ha^{-1}. As the surface flux is simply proportional to the concentration the mass deposited increases in proportion to concentration increase. Note in all the dry deposition calculations described in this report no attempt has been made to allow for the reducing flux of SO_2 due to the removal processes described. This amounts to about 5% per day for dry deposition plus a similar amount for photo-oxidation. Compared to the other assumptions necessary for the calculations to be made this effect is considered to be negligible.

The results of the ground level concentration calculations described above allow estimates of the deposition of SO_2 expected in the Kalgoorlie region. Figure 9 shows contours of annual dry deposition predicted from the gaussian plume model for the region surrounding Kalgoorlie. The outer contour shown corresponds to an annual deposition rate of 5 kg ha^{-1} with the 100 kg ha^{-1} value within ~ 5 km of the nickel smelter and ~ 1 km of the Gidji gold roaster. The 10 kg ha^{-1} isopleth encloses both SO_2 sources. Clearly, close to the sources the model predicts significant dry deposition of SO_2.

The results of the predictions of dry deposition for the long range calculations are as follows (see Figure 8). The isopleth corresponding to 1 μg m^{-3} occurs ~ 250 km in a westerly direction from Kalgoorlie and an annual dry deposition of ~ 1 kg ha^{-1} is predicted. The deposition ~ 5 kg ha^{-1} occurs closer to Kalgoorlie and within ~ 50 kms consistent with Figure 9. Consequently the prediction from both modelling procedures

suggest that the dry deposition of SO_2 has fallen to a value ~ 5 kg ha^{-1} yr^{-1} at a distance of ~ 50 km in any direction from the Kalgoorlie city centre.

4.3 Wet deposition of Sulphur

Estimating the wet deposition of sulphur is significantly more difficult than estimating dry deposition.

Pena et al (1982) have presented data to support the hypothesis that the sulphur content in rainwater is given by the equilibrium values corresponding to the rain drop surface SO_2 concentration in air and the aqueous concentration of HSO_3^-. Figure 10 shows the results of calculating the $[HSO_3^-]$ in rainwater as a function of ambient temperature and ambient SO_2 concentration assuming the rainwater has pH=5, the acidity being due solely to the presence of HSO_3^-. In reality, there will be dissolved HCO_3^- and organic acids which will influence both the pH and the level of HSO_3^-. (The square brackets denote concentration). The calculations are based on the equation

$$[HSO^-_3] = K_h K_1 [SO_2]/[H^+]$$

where $\text{Log } K_h = 1373.9/T - 4.159$

$\text{Log } K_1 = 868.3/T - 4.805$

and T is in degrees Kelvin

The values of $[HSO_3^-]$ in rainwater in Figure 10 can be used in conjunction with the SO_2 calculations shown in Figures 7 and 8 as well as rainfall information to estimate likely wet deposition.

Table 6 shows a summary of the rainfall data obtained from 12 sites surrounding Kalgoorlie for the 12 month period 1990/91. Calculations of the 'instantaneous' SO_2 concentrations for each site, equilibrium HSO_3^- concentrations assuming an average rainwater temperature of 15°C and resultant wet deposition of sulphur are also shown in Table 6. These calculations have been carried out by assuming that the SO_2 plume is always present at the particular receptor when the rain fell. While this cannot be the case for all sites the results of the calculation can be considered to be representative of a worst case. The values for deposition in Table 6 range from 1.6 kg ha^{-1} y^{-1} at Mount Magnet to 10 kg ha^{-1} y^{-1} at Menzies.

In order to estimate the fraction of rainfall during the 12 month period under study when the SO_2 plume was likely to be present at the time of the rainfall, we have proceeded as follows.

For each site and on each day, when rain was recorded, the location of the 4 trajectories for that day were inspected for their proximity to the rainfall site. This was done by assuming that if the trajectory direction from Kalgoorlie was within ±60° of the bearing of the rainfall site from Kalgoorlie then the rainfall at the site was affected by the presence of the plume. The results of this procedure are also shown in Table 6. The wet deposition has been corrected for the fraction of rain when the plume was in the vicinity of the rainfall site, and the values range from 0.3 to 3.1 kg SO_2 ha^{-1} y^{-1}. These may be

compared with detailed studies of rain at Katherine about 1000 km NW of Mt Isa (Galloway et al 1982, Likens et al., 1987). The average pH due to mineral acids was 5.06 and the S content (measured as SO_4^{--}) was highest when the air mass was continental rather than marine in origin. An average of 1.4 kg (SO_2 equivalent) ha^{-1} y^{-1} was deposited over a four year period, some of which was from sea salt.

The effect of using an average atmospheric and rain temperature lower than 15° is shown in Table 7 where the calculations have been carried out for 5 and 10°C. The colder temperature increases the solubility of SO_2 and hence the total deposition. An average ambient temperature of 5°C experienced by the rainwater approximately doubles the deposition compared to 15°C.

No account has been taken of the wet deposition of aerosol (acid) sulphate resulting from the photooxidation of SO_2. Whilst H_2SO_4 is the initial product, there will be some neutralisation from the (low) amounts of ambient NH_3 entrained into the plume. Consequently it is assumed that HSO^-_4 is the dominant form of sulphate. The size of the aerosol is < 1 μm and is poorly scavenged by rainfall. If the acidity of the rainfall is increased by the presence of HSO^-_4 then there is a drop in the amount of HSO^-_3 as the equilibrium $[HSO^-_3]$ is inversely proportional to $[H^+]$. For example if the rain pH were reduced to 4.5 by the presence of HSO^-_4, then $[HSO^-_4]$ would amount to 31μM/L and $[HSO^-_3]$ would be a factor of ~ 3 lower than the values listed in Tables 6 and 7 for $[HSO^-_3]$ alone at pH 5. At low SO_2 glc, the S deposition would be dominated by HSO^-_4. It is pertinent to enquire if there is likely to be a sufficient burden of aerosol acid sulfate to produce a pH of 4.5. At a distance of 500 km 5% of the SO_2 is oxidised to HSO_4^- (Williams et al. 1981) and $[SO_2]$ ~ 10 $\mu g/m^3$. If all the vertical burden of HSO^-_4 is scavenged by a 5 mm rainshower, then $[HSO^-_4]$ ~ 3 μM/L equivalent to pH > 5. Indeed it would take three times as much as HSO_4^- to produce a pH of 5 for a 5mm shower.

We conclude therefore that aerosol scavenging cannot produce a rain pH = 4.5, (except possibly for very brief showers though brief showers would be unlikely to scavenge much of the aerosol). The other possibility is aqueous phase oxidation of SO_2 by O_3 or H_2O_2. This would require about 50% of the SO_2 to be oxidised in the rain shower at a distance around 500 km from the source to result in rain of pH 4.5. However $[SO_2]$ is sufficently large closer in (< 500 km) that rain of pH 4.5 may result through aqueous phase oxidation.

In the light of the above discussion, we have only considered deposition of HSO^-_3 in rain of pH 5.

4.4 Reliability of the calculations

The results presented in this work are based on many assumptions. These need to be stated so that the reliability of the results may be appreciated.

First the assumptions associated with the gaussian plume modelling have been stated in section 3.1.1. Notwithstanding these assumptions Hayes and Moore (1986) have shown

that when the requirement of spatial and temporal resolution are relaxed the prediction of gaussian models are within approximately a factor of 2 of the maximum glc's recorded at a particular location. This is consistent with the annual average gaussian predictions, including shutdown periods, compared to the concentrations measured by the SO_2 monitors within the Kalgoorlie region.

The major assumption in the long range trajectory calculation is that the trajectories extend for 6 hours in a known direction and at the speed measured at the one site. Also that the wind field changes abruptly when the trajectory end point crosses the halfway mark between two pilot balloon sites and enters the wind domain of another pilot balloon site. These two assumptions are known from the work of Carras and Williams (1981b, 1988) to be reasonable when the synoptic situation is steady. However for a rapidly varying synoptic situation or local mesoscale flows it is likely that this assumption leads to considerable uncertainty. Counterbalancing this is the fact that at large distances from the sources e.g. 500 km the SO_2 concentrations are typically less than ~10 $\mu g\ m^{-3}$, even on an instantaneous basis. As a result the consequences of the trajectory assumption may not be as significant as at first seems likely. This conclusion is supported by the results of an intercomparison of four long-range transport models of SO_2 glc from the Netherlands (Derwent et al. 1989). These varied from detailed trajectory models such as the Norwegian EMEP model, already mentioned, to a purely statistical gaussian model using annual wind roses, at the receptor site with 1000 km back trajectories. The individual prediction of the annual average SO_2 glc were within ± 15% of the combined average of the four models. Further the confidence limit for the prediction of the Harwell model was assessed at 15%. The difference between the current study and that of Derwent et al. (1989) is that the latter studies modelled the impact of many widely distributed sources of SO_2 on a relatively small receptor area, i.e. the Netherlands. If, however, one looks how the results of the predictions compare with data from a particular monitoring site, then the EMEP model is within a factor of 2. (Iversen et al. (1989), quoted in Rolph et al., 1992). Consequently we believe that the modelled results of SO_2 glc due to the long range transport of SO_2 give a broadly accurate picture, but at any given location, they are probably no better than a factor of about 2.

The uncertainty in the dry deposition estimates depend on the uncertainty in the deposition velocity as well as the SO_2 concentration. However, over a long averaging period such as a year this is not likely to be important and accuracies are likely to be similar as for SO_2 glc.

The uncertainties in the wet deposition estimates are more difficult to quantify, and are greater than for the SO_2 and the dry deposition estimates.

It is clear that the results of the calculations presented in this report can only serve as an approximate guide to potential sulphur deposition. If the modelled annual deposition rates give any cause for concern, then the only method of confirming these estimates is by a monitoring program of direct measurement, particularly in areas which might be considered sensitive to sulphur deposition. The establishment of SO_2 monitors at about 50 km distance from the sources would provide an evaluation of the accuracy of calculations, when updated for the relevant meteorology. Similarly rainfall chemistry

collectors at selected locations within the agricultural region would provide direct measurements of the extent of wet deposition.

4.5 Effect of SO_2 GLC and Deposition on Crops and Pastures

In this section, we have attempted to provide a guide to possible impacts of the Kalgoorlie emissions on crops and pastures. To this end we have carried out a survey of recent literature on the effects of SO_2 on cereal crops. We emphasize that our conclusions, in this regard, are based not on specialist knowledge but on published data. Further advice should be sought.

Many of the studies of the effect of air pollutants on crops, prior to the 1980s, were carried out in closed chambers and their results have been discounted at least in terms of simulating actual field exposures. Since then, the use of open-top chambers or open-field reticulated fumigation systems have provided a better approximation to reality.

With open top chambers, an area of crop is surrounded by a cylindrical chamber, perhaps 3 m in diameter, and synthetic polluted air is dosed in at the bottom and escapes at the top. The enclosed crop is open to sunlight and rain. Reticulation systems do not have any containment devices but consist of a network of pipes laid on the ground over an area of some hundreds of sq. metres which release polluted air at points with a grid spacing of 2-3 m. The central portion of the crop is fumigated no matter what the wind direction and this is used for assessing pollutant effects.

Amundson and Kress (1990) studied the effect of SO_2 on winter wheat in open top chambers. The chambers were dosed intermittently and at different rates with SO_2 (and also O_3) over a 36 day period. Exposures were typically 4 h in duration with SO_2 concentrations in the different chambers being about 100, 400 and 1000 $\mu g/m^3$ along with a zero exposure chamber. When averaged over the 36 day experiment, the SO_2 exposure levels were about 5, 25 and 55 $\mu g/m^3$ respectively. No effect of SO_2 on crop yield was discernible from these experiments.

Olszyck and coworkers (Olszck et al., 1986, Bytnerowicz et al., 1987) exposed winter wheat to SO_2 continuously for up to 118 days in both open top chambers and a version of the reticulation system. The wheat was dosed with steady SO_2 concentrations ranging from about 10 to 400 $\mu g/m^3$, the first value being the 'zero' or background exposure case. They found no effect on yield when using the reticulation system, but when using the chambers found foliar injury to occur early in the growing period and that the yield was depressed by exposure to SO_2, although this latter conclusion was heavily weighted by the effect of the highest SO_2 exposure. Growth rates in the chambers were much higher than in the reticulation or outside ambient plots, illustrating the influence of even open top chambers on the enclosed environment.

An Australian study, carried out by Davieson et al., (1990) measured the effect of SO_2 on wheat in open top chambers, exposing the crop for 8 h each day to concentrations of <14, 133 and 266 $\mu g/m^3$ for 120 days. This translates to 5, 45 and 90 $\mu g/m^3$ when averaged over the entire experiment. Little effect was found at the intermediate exposure level but

the highest exposure (266 $\mu g/m^3$) caused reduced growth rate and a 25% reduction in grain weight. These observations indicate a greater sensitivity of wheat, or at least their cultivar (Eradu) to SO_2 than found in other studies.

A study designed to replicate SO_2 exposure typical of rural UK was carried out using a reticulation sytem over six growing seasons using two varieties of winter wheat and four varieties of winter barley (McLeod et al., 1991). SO_2 dosage rates were patterned to mirror 1h mean ambient SO_2 concentrations derived from monitoring data for central England.

24 h average dose rates ranged from 45 to 150 $\mu g/m^3$ with the ambient control plots subject to 25 $\mu g/m^3$. The results showed a decrease in crop dry weight during the growing season, which disappeared, however, by the time of final harvest. No trend was evident on the effect of SO_2 dose rate on yield of winter wheat. This was also the case for barley except at the highest SO_2 concentration (150 $\mu g/m^3$) which resulted in reduced yield. These workers suggested that the influence of SO_2 on yields and growth parameters may well be indirect and related to the effects on fungal and microbial pathogens.

Clearly, the situation with regard to the effects of air pollutants on crops is complex and not well understood. For a review of problems regarding evaluation of SO_2 dose-response relations see Roberts (1984). However, we can compare the SO_2 concentrations used in the above studies with that likely to result from the nickel and gold operations at Kalgoorlie. The wheat belt in WA starts at about 150 km west of Kalgoorlie.

The isopleth corresponding to an annual average SO_2 glc of 5 $\mu g/m^3$ doesn't extend more than 40 km from Kalgoorlie (Figure 7). Even on a 3 month average basis, more appropriate to the wheat growing season, the isopleth is no further than 60 km away (Figures 4-6). Over most of the wheat belt region, annual average glc are estimated to be between 0.5 and 1 $\mu g/m^3$ (Figure 8). Even short term (1h) peak concentrations from the combined maximum emissions are unlikely to exceed 200 $\mu g/m^3$ when 150 km away from Kalgoorlie. If the data quoted above concerning crop effects are any guide, it seems highly unlikely that SO_2 glc arising from the emissions around Kalgoorlie would have any adverse effect on the wheat growing region in WA. Indeed, 3 month average SO_2 glc only reach the 150 $\mu g/m^3$ within about 5 km from the sources, however, at this close range, high short-term glc may also be a concern with regard to crop growth. There is little agriculture in the vicinity of Kalgoorlie, so that it would be native vegetation which would be exposed to SO_2. Some eucalypt species are known to be very sensitive to SO_2 exposure (Murray, 1984).

The annual rate of deposition of SO_2 to the soil and vegetation can be compared to the rate of application of S as fertilizer to crops and pastures. The advent and use of high analysis fertilizers (double and triple phosphates) on cultivated land has considerably reduced the S input and the crops rely on maintaining the supply of mineralized S through the act of cultivation. This, however, is not inexhaustible and signs of S deficiency in cultivated land are beginning to appear. Indeed, in Europe, where steps have been taken

to reduce SO_2 emissions Schnug and Evans (1992) reported that S deficiency in cultivated land is now being observed.

In regard to improved pastures, typical application rates are about 10-20 kg/ha/y of S, which is equivalent to 20-40 kg/ha/y of SO_2 (Till, 1980). It is interesting to note that native pastures receive their S input from the atmosphere, the rate being less than 1 kg/ha/y (Till, 1980). Sea salt and volcanic fallout are considered to be the major contributors. In this context, it is possible that some benefit, in terms of S fertilization, arises from deposition from smelter emissions.

It can be seen from Figure 9 that the emissions from the smelting and roasting operations only lead to this level of application when less than 10 km from the sources. This rate has decreased to less than 5 kg/ha/y at 50 km away. Except close into the roaster or smelter, long term S deposition does not exceed typical rates of fertilizer application.

5. CONCLUSION

The results of modelling SO_2 glc show that for the 1990/1991 year in question, the annual average isopleth equivalent to 5 $\mu g\ m^{-3}$ did not extend beyond ~ 50 km from Kalgoorlie whilst for values higher than 20 $\mu g\ m^{-3}$ encircled Gidji and KNS at about 8 and 12 km respecitvely. On a seasonal basis, these isopleths can extend a little further out from the source.

Calculations of the total deposition of sulphur compounds from the KCGM and KNS sources have been carried out. These show that the values of dry deposition for locations within ~20 km from either source to positions close to the sources ranged from 10 kg $ha^{-1}\ y^{-1}$ to 100 kg $ha^{-1}\ y^{-1}$ within a few km of the sources. These values decreased rapidly from the sources so that at ~50 kms from the sources the dry deposition has dropped to 5 kg $ha^{-1}\ y^{-1}$.

Estimates of the wet deposition of SO_2 resulted in values of between ~0.3 to 6 kg $ha^{-1}\ y^{-1}$ depending on proximity to the sources, the amount of annual rainfall and average ambient temperature experienced by the rainwater.

Published data on the effect of SO_2 on crops, particularly wheat indicate little effect from average exposures of < 45 $\mu g\ m^{-3}$ on crop yields. These exposure levels only occur when within ~ 20 km of Kalgoorlie. The modelled annual average glc over the wheat belt region were in the range 0.5 to ~ 2 $\mu g\ m^{-3}$. It is concluded therefore that the SO_2 concentration from the combined roaster and nickel smelter emissions were unlikely to have significant impact on agriculture in the region. However we recommend more specialist advice be obtained on this matter.

Because of the number and complexity of the processes involved it is clear that the results of the calculations presented in this report can only serve as an approximate guide to potential sulphur deposition. If the modelled deposition rates, taking into account the uncertainties involved, give any reason for concern then the only method of confirming

the estimates is by a program of direct measurement, particularly in the areas which might be considered sensitive to sulphur deposition.

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Table 1 Emission details for the Gidji Roaster, Kalgoorlie Nickel Smelter and Oroya Roaster

Gidji Roaster	
Stack height	180 (m)
Gas exit temperature	613 (K)
Internal diameter	2 (m)
Gas flow rate (design max. value)	121 $m^3 s^{-1}$
SO_2 emission rate (design max. value)	10.8 (kg s^{-1})
SO_2 emission rate (1990/91 average)	3.6 (kg s^{-1})
Nickel Smelter	
Stack height	152 (m)
Gas exit temperature	550 (K)
Internal diameter	2.1 (m)
Gas flow rate	50-80 $m^3 s^{-1}$
SO_2 emission rate (1990/91 average)	7.6 (kg s^{-1})
Oroya Roaster	
Stack height	64 (m)
Gas exit temperature	513 (K)
Internal diameter	1.08 (m)
Gas flow rate	11 $m^3 s^{-1}$
SO_2 emission rate (design)	1.16 (kg s^{-1})

Table 2 Comparison of the annual average SO_2 concentration measured by the monitors in the Kalgoorlie region with the gaussian plume model predictions

Monitor	Measured Annual Average ($\mu g\ m^{-3}$)	Modelled Annual Average ($\mu g\ m^{-3}$)
Kalgoorlie Regional Hospital	9	6
Kalgoorlie Council Yard	13	9
Metals Exploration	17	8
Boulder Primary School	19	11
Boulder Shire Yard	16	16
Kalgoorlie Airport	13	13
Westrail Freight Yard	25	14
Carrington/Oswald Playground[1]	11	6
Hannans Golf Club[2]	8	7

[1] ~ 9 months valid data

[2] ~ 5 months valid data

Table 3 Frequency distribution of resultant 6 hourly trajectory directions from Kalgoorlie. Also shown is the average wind speed for each direction.

Trajectory direction	%	Wind speed ($m\ s^{-1}$)	Trajectory direction	%	Wind speed ($m\ s^{-1}$)	Trajectory direction	%	Wind speed ($m\ s^{-1}$)
0	0.48	4.8	120	1.51	11.8	240	1.93	8.5
5	0.76	4.6	125	2.34	8.7	245	1.38	7.1
10	0.28	6.7	130	1.31	9.4	250	2.00	6.4
15	0.62	7.0	135	1.24	9.3	255	1.17	5.8
20	0.96	4.1	140	1.03	8.8	260	1.24	7.2
25	0.48	6.4	145	1.38	9.9	265	1.93	5.0
30	0.89	5.5	150	0.89	7.1	270	1.38	6.6
35	0.41	8.0	155	1.24	7.1	275	1.72	6.7
40	1.03	6.8	160	0.55	10.7	280	1.72	7.0
45	1.17	6.9	165	0.69	7.8	285	2.13	6.6
50	1.10	8.0	170	1.38	9.4	290	1.65	8.1
55	1.10	8.1	175	1.31	9.7	295	1.86	6.8
60	1.45	7.0	180	1.31	8.5	300	2.00	7.4
65	1.31	7.6	185	1.03	9.7	305	2.75	7.6
70	1.17	9.9	190	1.24	9.0	310	2.48	7.7
75	1.58	11.1	195	1.31	8.2	315	2.75	6.9
80	1.72	10.7	200	1.93	7.7	320	2.06	6.8
85	1.24	12.0	205	1.38	8.5	325	2.55	6.2
80	0.96	9.4	210	0.89	7.7	330	1.65	6.2
95	1.38	10.1	215	0.96	7.3	335	1.38	6.0
100	1.93	10.7	220	1.24	7.1	340	1.17	6.4
105	1.79	11.4	225	1.24	8.1	345	0.83	6.3
110	2.27	9.1	230	2.06	6.2	350	0.55	4.6
115	1.45	8.6	235	2.00	6.2	355	0.76	5.5

Table 4 Frequency distribution of distance of trajectory endpoints from Kalgoorlie after a maximum elapsed time of 48 hours

	Distance from Kalgoorlie (km)				
	> 1000	> 800	> 600	> 400	> 200
Fraction greater than	0.635	0.697	0.803	0.897	0.966

N.B. On eight occasions the trajectory end points were within 100 km of Kalgoorlie after 48 hours elapsed time (i.e. on 0.5% of occasions).

Table 5 Total mass per unit area of SO_2 deposited to the ground for various values of SO_2 concentration for a deposition velocity of 0.3 cm s^{-1} over a period of 1 year

χ ($\mu g\ m^{-3}$)	M ($kg\ ha^{-1}$)
1	0.95
10	9.5
100	95

Table 6 Estimates of annual wet deposition of sulphur (as SO_2 equivalent) at the sites shown for 1990/91 and an ambient temperature of 15°C

Site	Rainfall (mm)	$\chi(SO_2)$ ($\mu g\ m^{-3}$)	$[HSO3^-]$ ($\mu M/l$)	Total possible Deposition (kg/ha)	Deposition* (kg/ha)
Mount Magnet	163	6.2	15.7	1.6	0.4
Geraldton	351	4.3	10.9	2.4	0.3
Dalwallinu	221	6.1	15.5	2.2	0.5
Perth	823	5.3	13.5	7.2	0.9
Albany	743	5.1	12.9	6.2	1.2
Experance	422	8.7	22.1	6.0	1.5
Merredin	248	9.6	24.3	3.8	0.9
Wagin	399	6.2	15.7	4.0	0.9
Forrest	235	4.6	11.7	1.7	1.0
Menzies	283	21.6	54.9	10.0	2.7
Laverton	147	11.6	29.5	2.8	0.7
Norseman	289	18.8	47.8	8.9	3.1

* Wet deposition corrected for the fraction of rain when the plume was in the vicinity of the site

Table 7 Estimates of annual deposition of sulphur (as SO_2 equivalent) at the sites shown for 1990/91 for ambient temperatures of 5 and 10°C

	T = 5°C		T = 10°C	
	$[HSO_3^-]$ (μ M/l)	Deposition kg/ha	$[HSO_3^-]$ (μ M/l)	Deposition (kg/ha)
Mount Magnet	30.1	3.1	21.7	2.2
Geraldton	20.9	4.7	15.1	3.4
Dalwallinu	29.6	4.2	21.3	3.0
Perth	25.8	13.6	18.6	9.8
Albany	24.8	11.8	17.8	8.5
Esperance	42.3	11.5	30.5	8.3
Merredin	46.7	7.4	33.6	5.3
Wagin	30.1	7.7	21.7	5.6
Forrest	22.4	8.2	16.1	2.4
Menzies	105	19.1	75.6	13.6
Laverton	56.4	5.3	41.0	3.8
Norseman	91.4	17.0	65.8	12.2

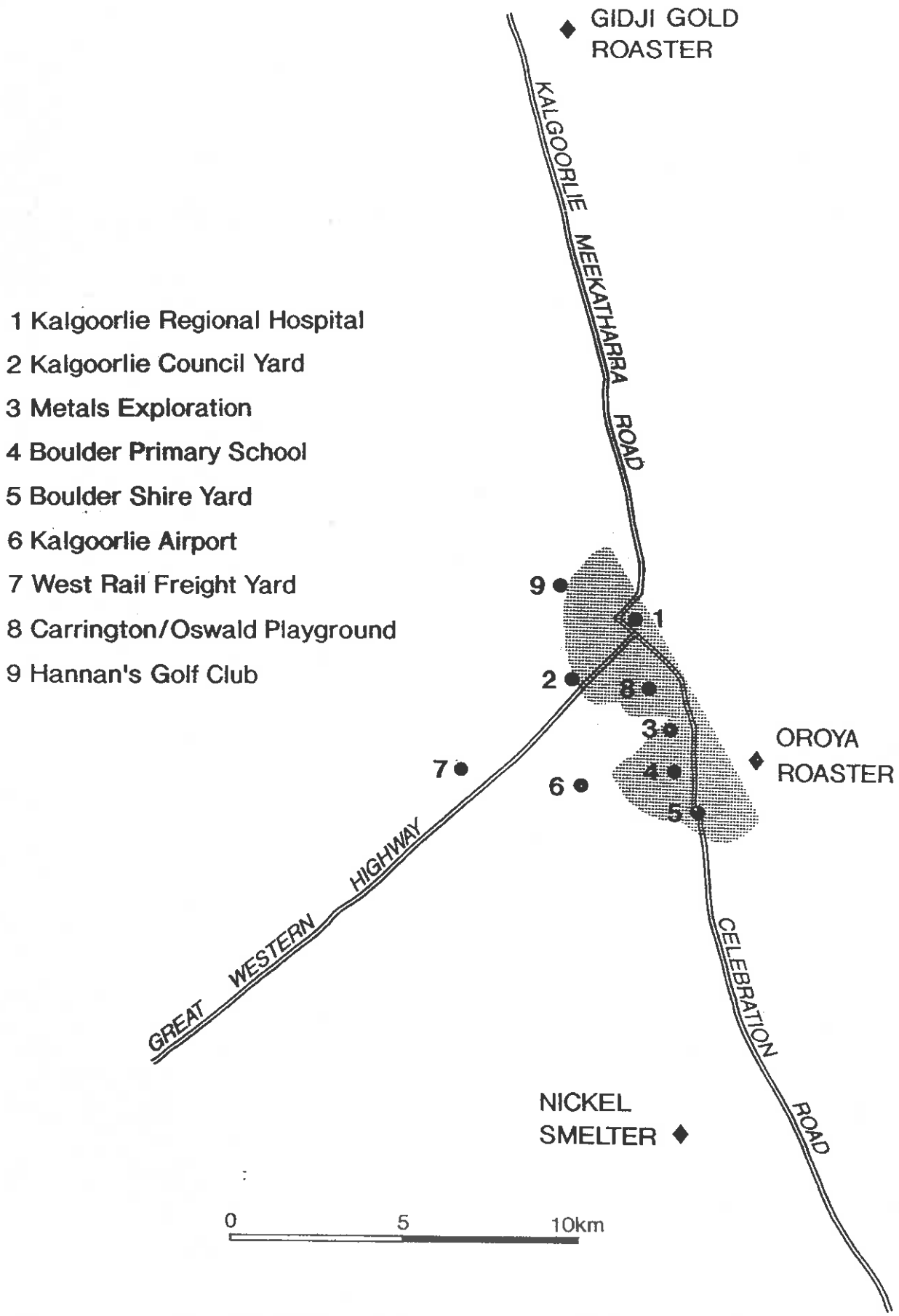

Figure 1 Location of the KCGM and Oroya roasters and KNS relative to Kalgoorlie.

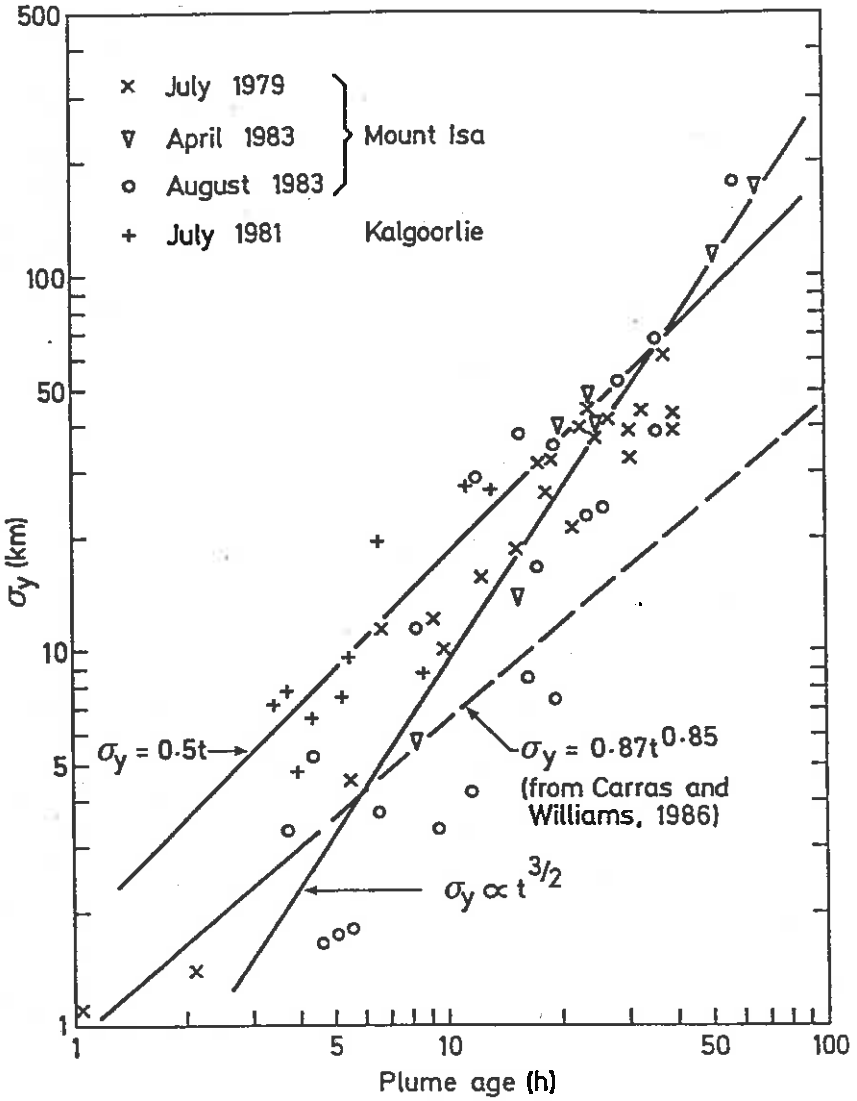

Figure 2 Measurements of σ_y as a function of travel time for distances up to 1800 km from the source (from Carras and Williams, 1988).

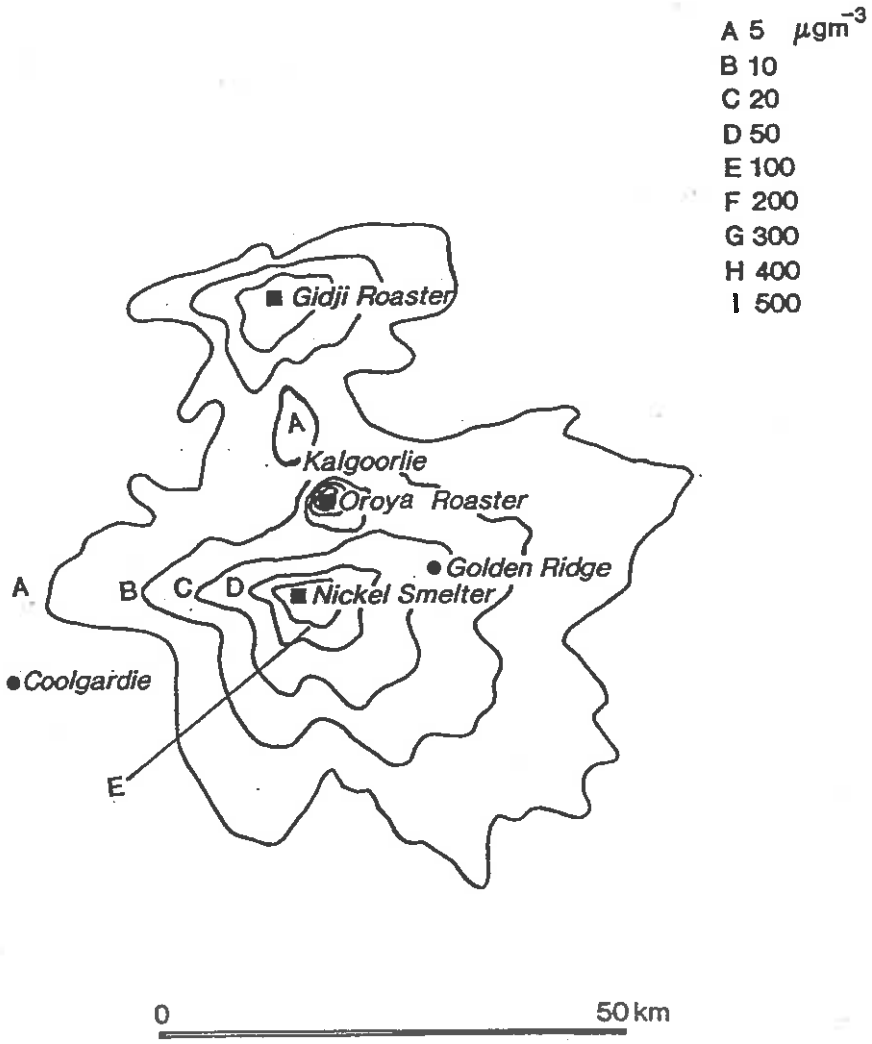

Figure 3 Isopleths of calculated 3 monthly average ground level concentrations of SO_2 for the period July 1991 and August and September 1990. The calculations were carried out using a gaussian plume model.

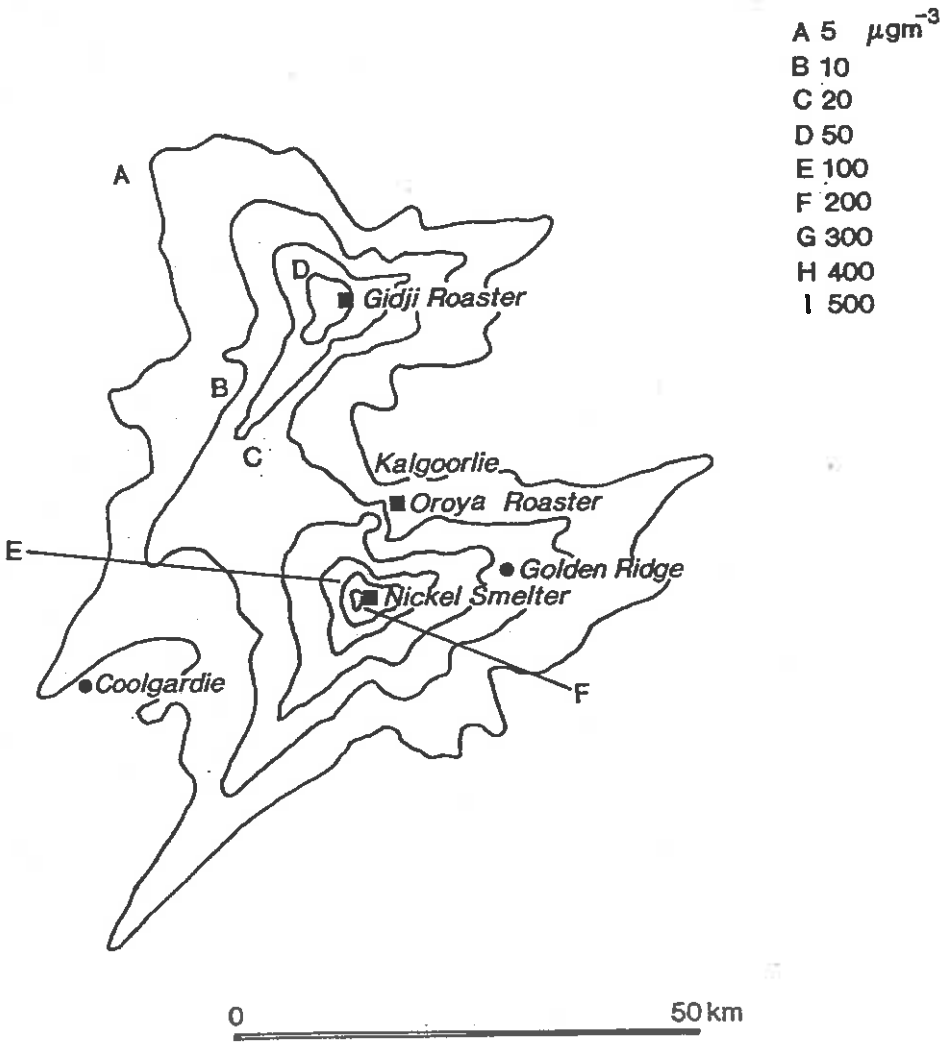

Figure 4 Isopleths of calculated 3 monthly average ground level concentrations of SO_2 for the period October 1990 to December 1990. The calculations were carried out using a gaussian plume model.

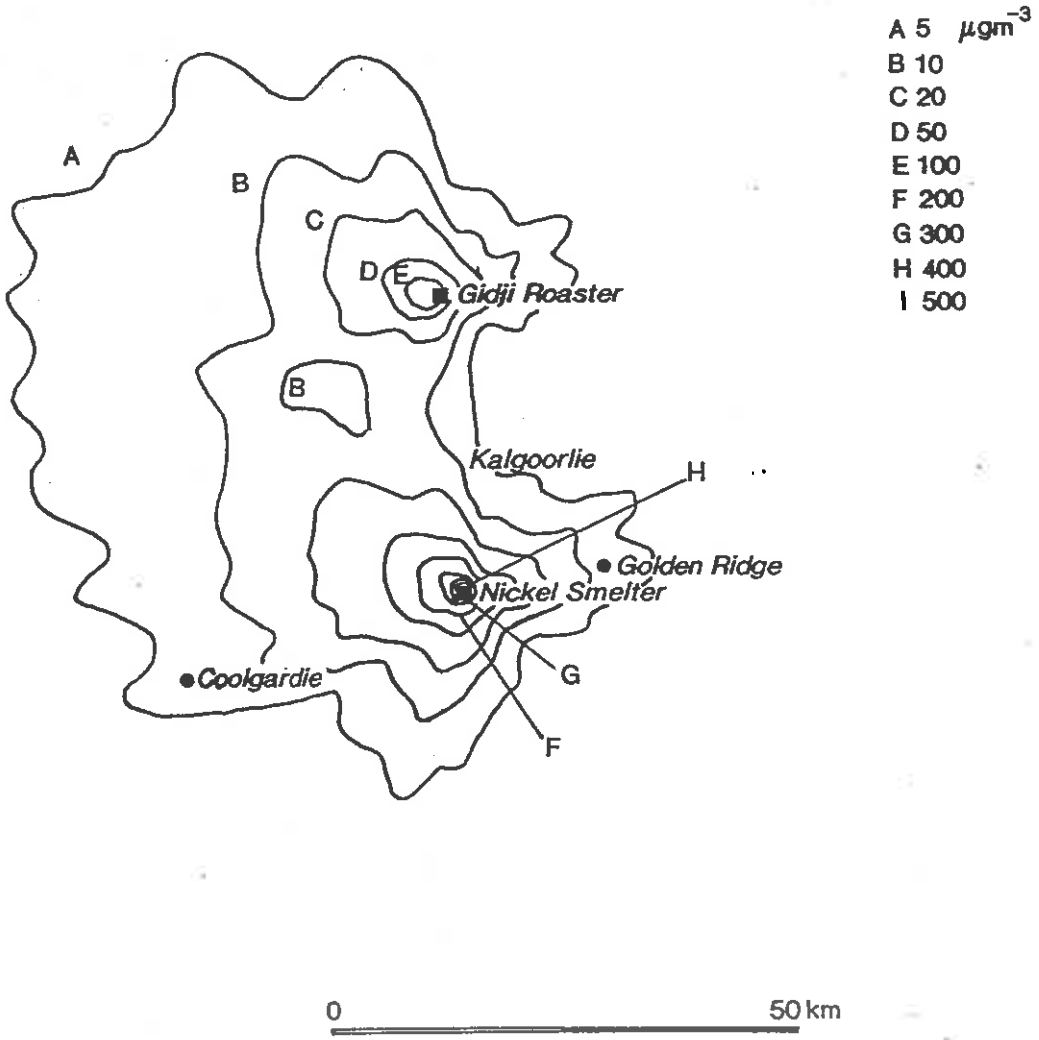

Figure 5 Isopleths of calculated 3 monthly average ground level concentrations of SO_2 for the period January 1991 to March 1991. The calculations were carried out using a gaussian plume model.

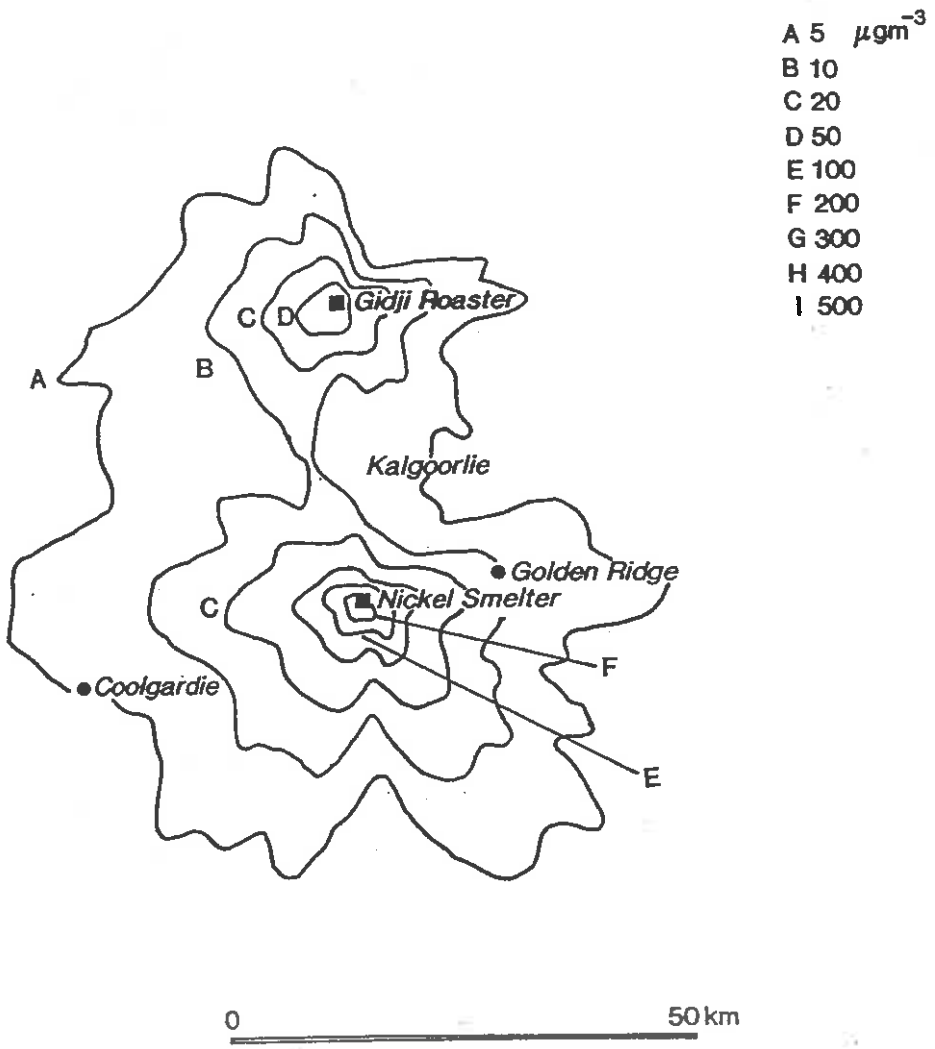

Figure 6 Isopleths of calculated 3 monthly average ground level concentrations of SO_2 for the period April 1991 to June 1991. The calculations were carried out using a gaussian plume model.

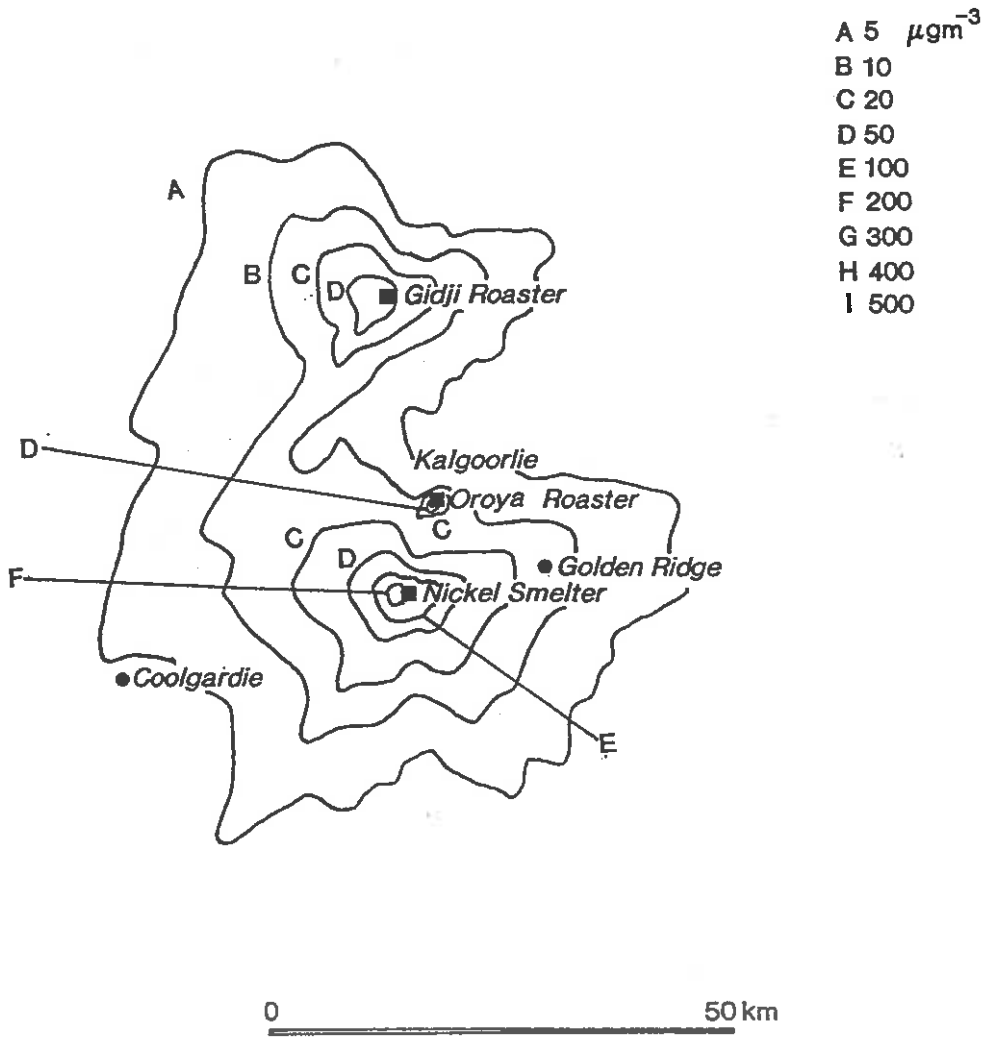

Figure 7 Isopleths of annual average ground level concentrations of SO_2 for the period August 1990 to July 1991.

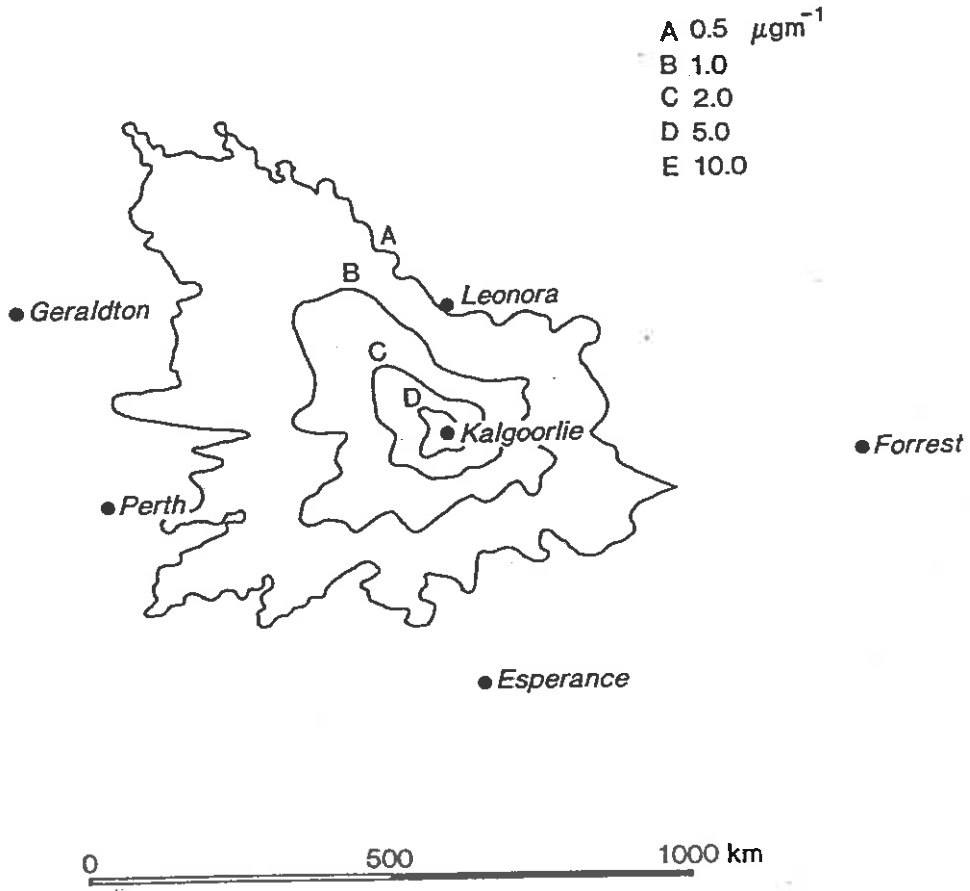

Figure 8 Isopleths of annual average ground level concentrations of SO_2 for the period July 1990 to June 1991. The calculations were carried out using the long range puff model.

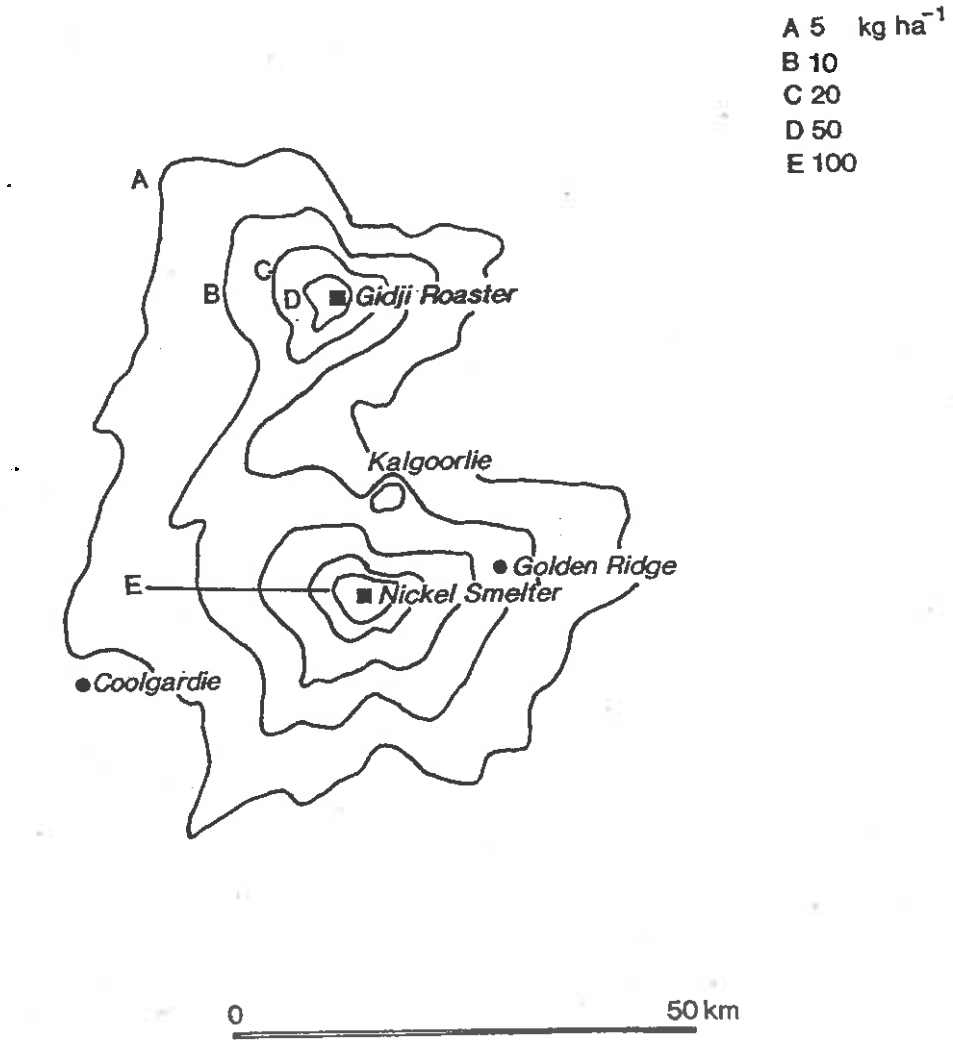

Figure 9 Contour of annual dry deposition of SO_2. The calculations are based on the results from Figure 7.

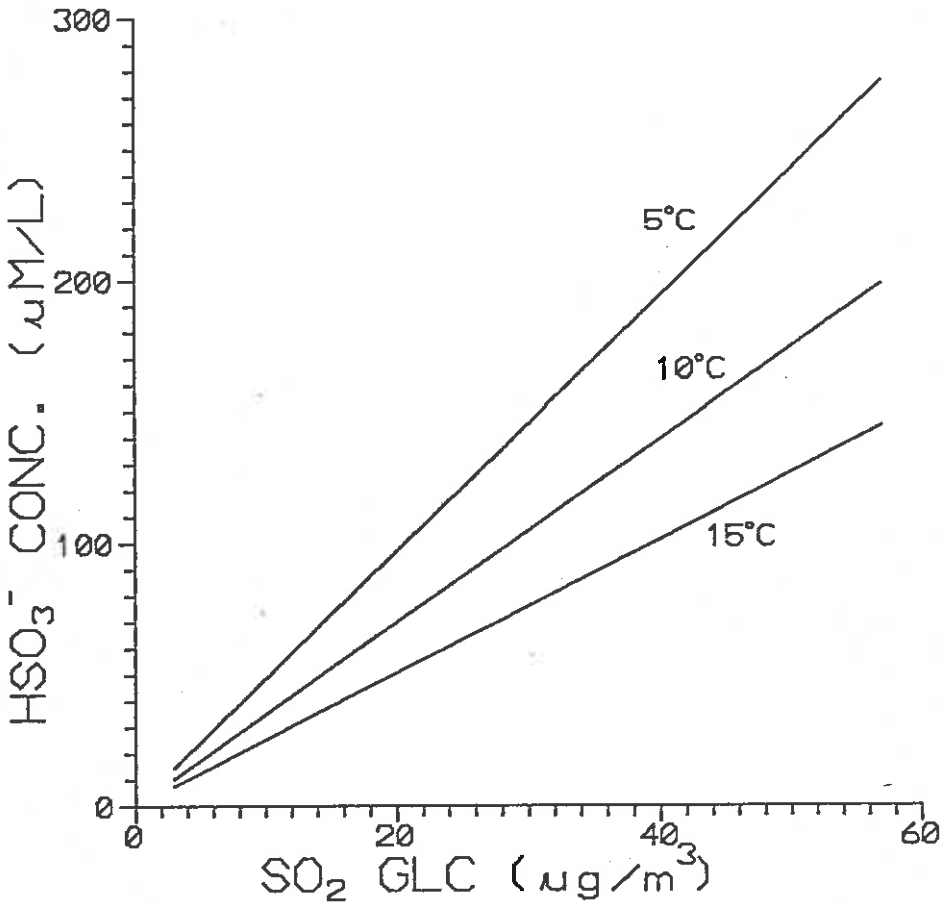

Figure 10 Calculated values of $[HSO_3^-]$ in rainwater as a function of SO_2 concentration in air for three values of rainwater temperature.