A SCAVENGING MODEL ANALYSIS AROUND A LARGE COAL-FIRED POWER PLANT IN NEW DELHI WITH A PARTICULAR REFERENCE TO THE SCAVENGING ACTION OF THE MONSOONAL RAINS

S. Ghosh and M.P. Singh

Centre for Atmospheric and Fluids Sciences
Indian Institute of Technology, New Delhi-110016.

Abstract. There have been reports in the recent past about the problem of SO_2 pollution over India. Some of them have even stated that corrosion of the Acropolis in Athens is now matched by the corrosion of the Taj Mahal in Agra. Mathematical models and experimental analyses have been undertaken to address the problem of SO_2 pollution over selected Metropolitan cities in India.

An important feature revealed from these model studies is that most urban air quality models in India grossly over predict ambient SO_2 levels during the monsoon period. This is because washout calculations are not featured in these models. In this paper we have tried to demonstrate the efficacy of the south-west monsoon rains to a scavenge a soluble pollutant like SO_2 from an urban environment. India in general does not face the acid rain threat yet. However, results of rainwater analyses show that low pH of precipitation does occur at isolated pockets downwind of major industries and power plants. In this paper we have determined the extent of acidic deposition in the near field of a large coal-fired power plant in Delhi. SO_2 concentration profiles, with and without washout calculations have been shown. Probable periods of the year and the areas within the meteroplition regions of Delhi which could be worst affected by acid impaction have been identified on the basis of the model simulations with mean climatological data. Model computations show that maximum pollution is brought in to the city from this power plant during the month of October. The hourly GLC often exceeds 1000 μg m^{-3} which is quite a close to the federal standard of 1100 μg m^{-3}; likewise the acid deposition flux is greatest during the month of August and is of the order of 50 μg m^{-2} s^{-1} at a downwind distance of 1 km.

The nature of the washout coefficient during the monsoon pre and post monsoon periods in relation to the relative importance of the atmospheric variables concerned has been investigated. The role of individual monsoonal showers to scavenge SO_2 has been discussed.

This is perhaps the first work of its kind from India wherein representative washout coefficients have calculated and subsequently featured as washout effects in an urban air pollution model. Results show that this parameter could be as high as 16.03×10^{-5} s^{-1} during August and as low as $1.1 \times 10^{-6} s^{-1}$ in April.

Keywords. Scavenging, washout coefficients, Ground level concentrations, Acid deposition flux.

INTRODUCTION

In recent years we have witnessed an increased awareness of a potential rise in the acidity of precipitation. This phenomenon, has prompted considerable concern for ecologists in the regions of suspected maximum impact such as the Northeastern United States, South eastern Canada, and Scandanavia . It is generally recognised that "acid rain" is primarily the result of long range transport and transformation of combustion products from industrial and transportation sources.

Systematic work on measuring rainwater acidity in India began with Mukherjee (1957) who reported pH measurements of Calcutta rainwater and subsequently of Bombay rainwater. In one of the measurements near Calcutta, Mukherjee(1957) found that rainwater showed some acidity when the trajectory of air over the sample collection site was from the highly industrial area

Routine measurements on rainwater acidity in India have been carried out from 1982 onwards. These studies are being done by the Bhaba Atomic Research Centre (BARC), Bombay and also by the network of background pollution monitoring (BAPMON) stations established in India by the World Meteorological Organisation (WMO). The results of these measurements indicate that rainwater acidity in India has not so far reached alarming levels . The high dust loads in the Indian atmospheres may be providing enough material to neautralise the acids even when they are present. Sequira(1982), Das et. al(1981) and Handa(1969) measured the pH of rainwater at several places in India and came to a similar conclusion.

Apart from the measurement of Mukherjee (1957), more recently high acid content of rainwater has also been observed in small pockets downwind of some factories and thermal power plants. The earlier work by the BARC group in Bombay had shown that areas like Trombay and Chembur has acidic rains (with pH of 4.45 and 4.85 respectively) during 1974.

More recently experts attending a National Conference on pollution management have warned against the possibility of acid rain over Agra and said that its effect on the Taj Mahal will be disastrous . Acid rains would hit India in 10 years from now, if industrial units continue to burn coal at the present rate.

The above discussions highlight the fact that even though rainwater acidity in India has not yet reached alarming levels at most places, in the immediate vicinity of factories there still is an acid rain threat. Our interest in rainwater acidity, is therefore confined to its immediate effects on materials of construction and the preservation of stone monuments in the close vicinity of polluting sources. One of the first requirements in this direction, is the assessment of the current situation, so that if conditions are found to be deteriorating measures can be taken to limit the emissions. One of the ways by which this can be done is by undertaking accurate quantitative measurements with a large network of monitoring stations. However, this being a very elaborate and expensive affair, involving a lot of skilled manpower, the only other viable alternative left is by taking recourse to regional scale mathematical models. These models are quite capable of providing 'quick look' estimates of the air-pollution status around a specific region and are also fairly inexpensive to implement.

Having elaborated upon the justification for the use of mathematical models for assessing rainwater quality in a given region, the question of the choice of a suitable model still remains. Both Lagrangian and Eulerian methods are used to assess the transformation and transport of SO_2 in the atmosphere.

For example Charmichael and Peters (1984) have proposed an Eulerian combined transport/Chemistry/removal model that describes the regional distribution of SO_2 and sulphate.

The mathematical basis for this Eulerian model is the coupled 3D-advection-diffusion equation. The set of equations is numerically solved using a Crank-Nicholson Galerkin Method. This model is extremely elaborate and entails a large expenditure on expensive computer time and so is not very suitable for Indian conditions. Likewise, the Univ. of Michigan Atmospheric contributions to Inter-regional Deposition (ACID) model is also fairly elaborate. Both these models require detailed meteorological inputs (including variation of Topography) and chemical kinetic data. Such detailed information are often not available. The choice of a model depends on the question or hypothesis being tested and the accuracy of the answer needed. In the N.E. United States, Canada and some parts of Europe where 'acid rain' is a potential threat to everyone concerned, it is justified to use elaborate models like the ACID model. For Indian conditions, mainly for a preliminary assessment purpose it seems most appropriate to use simple analytical models, with an accurate input of relevent meteorological parameters.

With the above perspectives, we propose to undertake a scavenging model analysis around the Indraprastha Power Plant situated in New Delhi. The chief objectives of undertaking this study are:

a. To demonstrate the efficacy of the South west monsoonal rains to scavenge a soluble pollutant like SO_2 from an urban environment.

b. To recommend the use of washout calculations in all Indian urban air quality models. Without such calculations, these models will grossly over predict ambient SO_2 levels during the months of July to September.

c. To determine the extent of acidic deposition within the power plants near field (within 10 km radius).

d. To evaluate the relative importance of the atmospheric variables concerned.

MATHEMATICAL FORMULATION

Level terrain is assumed in our analysis. We consider the steady state form of the atmospheric advection-diffusion equation with washout effects:

$$D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} - u \frac{\partial c}{\partial x} - \beta c = 0 \qquad (1)$$

Here, x,y,z are the horizontal downwind, crosswind and vertical coordinates respectively; u is the constant average wind speed, and β is the washout coefficient for SO_2, c is the SO_2 concentration at (x,y,z), and D_y and D_z are the constant eddy diffusivities in the crosswind and vertical directions, respectively.

For a continuous point source of strength Q located at (x = 0, y = 0, z = h), the boundary conditions are given by:

$$c(0,y,z) = \frac{Q}{u} \delta(y)\, \delta(z-h) \qquad (2a)$$

$$c(x,\pm\infty,z) = 0 \qquad (2b)$$

$$D_z \frac{\partial c}{\partial z} = 0 \text{ at } z = 0 \text{ and } H \qquad (2c)$$

we assume that the pollutant concentration is zero far away in the lateral direction and that there is no pollutant flux at the ground at z = 0 and at the top of the mixed layer at z = H.

For constant D_y and D_z, the exact analytic solution of the diffusion equation was first given by Monin (1959) and later by Smith (1962), Scriven and Fisher (1975), Rao (1975) and Ermak (1977). These solutions due various authors, though basically similar, differ somewhat due to different source conditions, pollutant species and other assumptions used in their studies.

In this paper the main emphasis will be on wet scavenging and on the extent of wet removal with monthly variations of the washout coefficient. We have not considered dry deposition effects because it is well known that washout when it occurs is a more effective mechanism for removing SO_2 than dry deposition effects. It is also worth pointing out that rainfall rates are highly variable from January through December over India. During the monsoon periods the intensity of rainfall for an individual shower could be of the order of 25 mm/hr. This is a common occurrence over India unlike the situation in Britain where typical rainfall rates correspond to about 1 mm/hr for a heavy shower . No work is reported in literature from India where representative washout coefficients have been calculated based on Indian climatological data; neither have they been featured as washout effects in any ubran air quality model. As a result these models have grossly over predicted ambient SO_2 levels during the monsoon months (Gupta and Padmanabhamurty (1984)).

ANALYTICAL SOLUTIONS

Equation (1) is solved by applying Laplace transforms w.r.t. 'x', Fourier transform w.r.t. 'y', and Finite Fourier cosine transform w.r.t., 'z'. Using the boundary conditions (2a-2c), we obtain the following solution

$$c(x,y,z) = \frac{Q\, e^{-y^2/2\sigma_y^2}\ e^{-\beta x/u}}{uH\ \sqrt{2\pi}\ \sigma_y} [1+2 \sum_{n=1}^{\infty} \times \cos\frac{n\pi z}{H} \cos\frac{n\pi h}{H}\ e^{-\frac{D_z\, n^2\pi^2}{H^2}\frac{x}{u}}] \quad (3)$$

where $$\sigma_y^2 = 2D_y \frac{x}{u} \quad (4)$$

In order to facilitate the practical application of the analytical solution the eddy diffusivity D_y is expressed in terms of σ_y, the standard deviation of the crosswind Gaussian concentration distribution.

(1) Plume Trapping:

It has been assumed that neutral conditions prevail while it is raining and it is reasonable to estimate σ_y as:

$$\sigma_y = 0.36\ x^{0.86} \quad (5)$$

(Smith and Singer(1966))

Following the current practise in EPA models mainly for a neutral atmosphere, the mixing depth should be included in the algorithm. This is usually done through calculation of multiple eddy reflections both from the gro ground and the stable layer aloft, when the plume is trapped between these two surfaces. Our solution (3) can be easily recast into a form where the above effect is immediately apparant. By introducing the parameter $\sigma_z^2 = 2D_z\ x/u$ and the substitutions $\nu = \frac{1}{2}\left(\frac{\pi\sigma_z}{H}\right)^2$; $\tau = \frac{\pi}{2H}(z \pm h)$ in the relation:

$$1+2\sum_{n=1}^{\infty} e^{-n^2\nu} \cos 2n\tau = \sqrt{\frac{\pi}{\nu}} \sum_{n=-\infty}^{\infty} e^{-(\tau-n\pi)^2/\nu}$$

the solution (3) can be expressed in the form:

$$c(x,y,z) = \frac{Q\, e^{-y^2/2\sigma_y^2}\ e^{-\beta x/u}}{\sqrt{2\pi}\ u\sigma_y\sigma_z} \times [\sum_{n=-\infty}^{+\infty} e^{-(z+h-2nH)^2/2\sigma_z^2} + e^{-(z-h-2nH)^2/2\sigma_z^2}] \quad (6)$$

Multiple reflections are now immediately apparant in the above expression.

(ii) Surface Deposition Flux:

From (3), the precipitation induced flux of effluents to the ground at any downwind distance, x, is easily obtained as:

$$F(x,y) = \frac{\beta\ Q e^{-\beta x/u}\ e^{-y^2/2\sigma_y^2}}{\sqrt{2\pi}\ \sigma_y u} \quad (7)$$

and along the plume-centre-line, where y = 0,

$$F(x,0) = \frac{Q\beta e^{-\beta x/u}}{\sqrt{2\pi}\sigma_y u} \quad (8)$$

This is the amount of SO_2 deposited per unit time per unit surface area along the plume centre-line and hourly, monthly or yearly estimates at a given downwind distance from the source in a given wind direction can be easily made.

IMPLEMENTATION OF THE MODEL

A computer program has been developed for the ICL 2960 system available at the IIT Delhi. The data used in this model are given in Table 1.

The SO_2 scavenging coefficients are computed after the method outlined by Samson and Small(1984) and is given by

$$\beta = 5 \times 10^4\ P/H \quad (9)$$

where P is the precipitation rate (mm per hour) and H is the mixing height.

This method was adopted in preference to the more common method of adopting a constant β value, because in the present approach the scavenging coefficient is a function of both the precipitation rate and the mixing height - both of which are highly variable under Indian conditions. It will therefore just not suffice to have "one representative scavenging coefficient". We have considered the seasonal variation of the mean mixing depths over Delhi. The vertical eddy diffusion coefficient was taken as 10 $m^2\ s^{-1}$.

The power plant in question is the Indraprastha Power Plant located in the east of Delhi city. The average amount of coal burnt per day is 3000 metric tons. The sulphur content of Indian coal is .5% and with these informations the total estimated source strength of SO_2 due to coal burning at the Indraprastha Power Plant is 1.19×10^6 g/hr or 331 gs^{-1}.

The effective stack height (plume rise plus physical stack height) under neutral conditions was found to be about 150 m.

RESULTS AND DISCUSSIONS

(i) Ground level concentrations: (GLC)

The ground level (z = 0) plume centreline (y = 0) concentrations are shown in Figure 1 as a function of the downwind distance x for the months of January (winter), May (summer), August (monsoon) and November (autumn). Concentrations are also shown without washout calculations for the sake of comparisons.

During the winter months of December, January and February the maximum hourly GLCs are less than 650 μg m^{-3} and the wind direction is north-westerly. Washout effects are also not significantly pronounced during these months and the pollutants are blown away from the city's main lands. During October and November the maximum hourly SO_2 concentrations are of the order of 1000 μg m^{-3} upto 1 km downwind. (Most federal standards specify that the hourly concentration of SO_2 should not exceed

TABLE 1: MODEL INPUT PARAMETERS

	Mixing Depth H m	Wind Speed U ms^{-1}	Wind Direction	Rainfall rate mmh^{-1}	Washout Coefficient β s^{-1}
JAN	760	3.22	NW	0.8	1.47×10^{-5}
FEB	1215	4.36	NNW	0.33	0.38×10^{-5}
MAR	1356	4.47	NNW	0.55	0.56×10^{-5}
APR	1500	5.07	SW	0.12	0.11×10^{-5}
MAY	1462	4.95	W	0.64	0.61×10^{-5}
JUN	1545	6.40	NNE	2.07	1.88×10^{-5}
JUL	1050	3.40	SE	6.2	8.27×10^{-5}
AUG	952	2.89	ESE	10.9	16.03×10^{-5}
SEP	997	2.66	W	6.2	8.71×10^{-5}
OCT	1354	2.03	NE	0.97	1.00×10^{-5}
NOV	1457	2.22	NNW	0.13	0.125×10^{-5}
DEC	561	2.85	NW	0.64	1.597×10^{-5}

(The data presented above are mean hourly averages based on five years data)

1100 μgm^{-3}). During the month of October, the prevailing wind direction being NE aggravates the situation further, because SO_2 is blown into the city directly. Important structures like the Supreme Court buildings, the National Stadium and the India Gate are thus directly affected.

The summer months of March. April,May and June are characterised by relatively lower GLCs. The boundary layer is mostly in a state of vigorous mixing. During these months the mixing depths are quite large.

The months of July, August,and September are characterised by the monsoonal rains. Scavenging effects are significantly pronounced during the month of August when the mean rain fall rate is about 11 mmh^{-1}. This is clearly evident from the Figure 1.

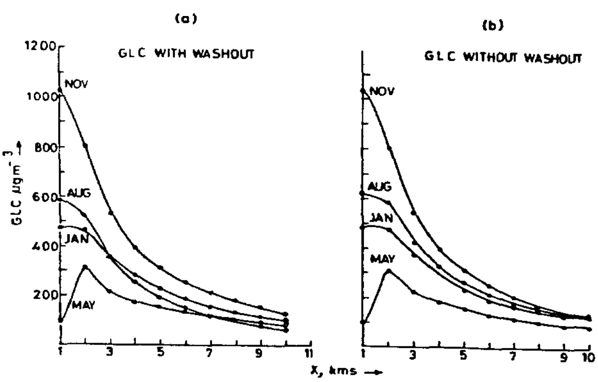

Fig. 1: Ground Level concentrations with and without washout effects at different downwind distances.

In Table 2 we have tabulated the GLCs, with and without washout effects for the month of August. We find that unless washout calculations are featured in the model, the extent of over prediction is quite significant. This effect is more pronounced as one moves further downwind from the power plant. This is because as the plume progresses downwind the extent of scavenging keeps on increasing (we have assumed that the scavenging action is continuous within the one hour period) and by the time it has advanced 10 kms a significant fraction of SO_2 is washed down by the falling rain.

TABLE 2: GLCs WITH AND WITHOUT WASHOUT EFFECT

X, Km	GLC in August μgm^{-3} with washout	GLC in August μgm^{-3} without washout	% of over-prediction
1	593.6	627.5	5.7
2	528.8	590.4	11.6
3	354.4	418.6	18.1
4	259.5	324.1	24.9
5	196.6	259.5	32.0
6	153.5	214.2	39.5
7	122.2	180.3	47.5
8	99.2	154.7	55.9
9	81.8	134.8	65.5
10	68.2	118.9	74.3

During the months of July and August the wind is South easterly. A lot of SO_2 is scavenged by the falling rain because of the fairly intense precipitation rates. Structures most vulnerable so far as polluted rain is concerned are Vikas Minar (Office of the Delhi Development Authority), Lady Hardinge College, Maulana Azad Medical College, Lok Kalyan Bhawan etc. Rainwater measurements should be done at atleast one of these sites to study the effects of anthropogenic emissions on the precipitation quality. Unfortunately, todate not even one sampling site is chosen around any one of these identified localities. Should acid rains ever hit the city due to increased SO_2 emissions from the I.P power plant, then these are the probable places where the effects would be the most pronounced.

(ii) Effect of individual monsoon storms:

Individual storms can wash down most of the pollutants. Storms during the monsoons are characterised by very high rainfall rates. The storm discussed here had a rainfall rate of the order of 50 mmh^{-1} ((August 1960). The scavenging effects of a monsoon storm on the GLC is depicted in the Figure 2. It is clear from this figure that the fall in the GLC due to washout in a storm is more pronounced than in the case of mean hourly washout.

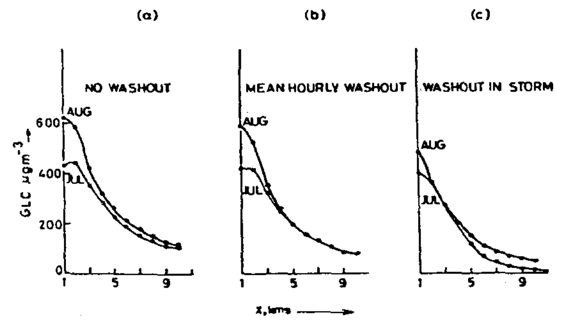

Fig. 2: Portrayal of scavenging effects of individual storms on the GLC during the monsoons.

(iii) Wet removal flux of SO_2 during the monsoons:

Expression (8) was directly used to estimate the precipitation induced flux of SO_2 to the ground. As expected this is highest for August because of the large value of ' ' and a comparatively low value of the mixing height, H, and ranges from about 50 $\mu gm^{-2} s^{-1}$ at a downwind distance of 1 km to about 11 $\mu gm^{-2} s^{-1}$ at 10 kms downwind, along the plume centre line. From the expression (8) it is clear that the variation of the wet removal flux with downwind distance is exponentially decaying, hence these profiles are not explicitly shown.

(iv) Vertical profiles of the ambient concentration during the monsoons:

The most important observation in this connection is that even during a fairly severe strom (rainfall rate $\sim$ 50 mmh^{-1}) the shape of the vertical profiles essentially remain unaltered. One observes the familiar Gaussian profile (with a peak concentration level centered around the effective stack height) in the near field (1 km downwind). Effects of ground reflection are apparant as one proceeds further downwind. These profiles are shown in Figure 3.

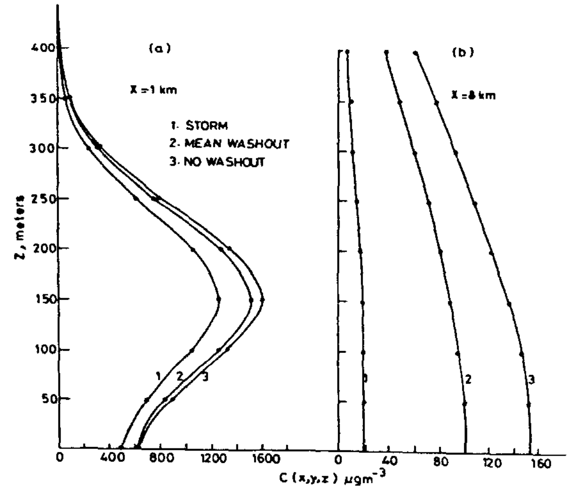

Fig. 3: Vertical profiles of the ambient concentration during the monsoons (August).

LIMITATIONS AND ADVANTAGES

A constant diffusivity in the vertical is taken throughout. This is a major limitation, and the effects of a variable diffusivity profile will be featured in a subsequent work. Another major limitation of this model, as is the case in common with most of the simple dispersion models, is its inability to allow for the change in wind velocity with height above the surface. Chemical transformation processes and dry deposition effects have also been disregarded.

Inspite of all these limitations this model has been put to practical use as a result of simulation with mean climatological data. The main points are summarised below.

1. During the months of July and August a lot of SO_2 released from the I.P. Power Plant is scavenged by the monsoonal rains. The wind direction is South easterly and the pollutants are brought in directly to important areas within the Metropolitan regions of Delhi city. The chances of precipitation contamination within the power plant's near field are the greatest in these areas. Any proposed field studies to monitor rainwater quality in Delhi must consider sampling sites at these regions.
2. Scavenging effects are significantly pronounced during the months of July, August and September. Any urban air quality model must therefore feature washout effects during concentration simulations at least during these months; otherwise the model will grossly over-predict concentration levels during these months. To date, no urban air quality model in India, features such calculations.
3. Being an analytical model the computational expenses incurred are much lower than a comparable numerical model.

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