EnvironmentAsia
The international journal published by the Thai Society of Higher Education Institutes on Environment

Available online at www.tshe.org/EA
EnvironmentAsia 4(2) (2011) 1-8

Establishing the Efficacy of the Cleansing Action of Tropical Evergreens: A Modeling Analysis of Asia's Largest Lignite Based Power Plant

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Abstract

Developing nations of Asia will continue to rely on fossil fuels to meet their energy needs for years to come. In this context, mitigation of air pollution due to thermal power plant emissions assumes special significance. The Neyveli Lignite Corporation (NLC)- Asia's largest Lignite based Thermal Power Plant took a visionary step in this regard, four decades ago, via a massive afforestation program involving 17 million evergreen trees. These trees, now fully grown, play an important role in abating air pollution in the NLC town ship which is home to 128,133 people.

This first study quantifies the cleansing action of these evergreens by employing a tailor-made atmospheric dispersion-deposition model which accounts for unique regional factors- the year round high solar insolation, high temperatures and the convective nature of the atmospheric boundary layer. We model the dispersion of SO_2 emitted from multiple elevated stacks (typical source strengths are 300 g/s) and its deposition onto the evergreen canopy. Deposition is quantified in terms of the universal deposition velocity parameterization via inferential-resistance modelling of the transport pathways. Results indicate that considerable amount of pollution is deposited onto the canopy year round. In addition active cleansing of the atmosphere takes place over regions not directly in the path of SO_2 emissions but nevertheless affected by residual pollution. This is relevant to large areas of NLC due to the wind pattern which involves a daily wind direction shift in the afternoon as well as several periods of calm.

The present model has been coded to be made portable and can serve as a decision making tool in the screening, scoping and baseline analyses of Environmental Impact Assessment studies.

Keywords: dry deposition; dispersion model; SO_2 emissions; afforestation; deposition velocity

1. Introduction

The developing nations of the World are heavily reliant on fossil fuels to meet their energy requirements. India is no exception, with coal generated thermal power accounting for a majority of electricity production in the country. While the emission of harmful gaseous pollutants from power plants is inevitable, it may be possible to mitigate their harmful effects on the environment. Afforestation has long since been associated with improved air quality due to the absorption of polluting gases by trees. However, what affect would 17 million trees have on a power plant which emits around 3900 g/s of SO_2 every day of the year, 24×7? No study on this scale has been conducted thus far- especially not in India where the unique climatic conditions and vegetation make borrowing results from mid-latitude regions unsatisfactory.

The subject region of study is the Neyveli Lignite Corporation (NLC) located in the Cuddalore district of Tamil Nadu, India. NLC is a large lignite based thermal power plant which covers an area of about fifty-four square km and produces 2,490 megawatts per annum of electricity. It has two power plants: Thermal power plant (TPS) 1 and its expansion and TPS2. Thirteen elevated stacks continuously spew out SO_2 containing emissions into the atmosphere. Details of these stacks are given in Table 1.

NLC is home to 128,133 people and the township, located close to TPS1, is bound to receive emissions from the stacks. Thankfully, the founding fathers began a massive afforestation program which today has resulted in an extensive tree cover. In this paper we investigate the role of these trees in maintaining air quality and providing healthy living conditions in and around NLC. A map of the region of interest and an aerial photograph from Google Earth is shown in Fig. 1. The tree cover, especially in the township, is clearly visible.

2. Parameterization of Dry Deposition to vegetation

The evergreen canopy is considered to be an irreversible sink for SO_2 and the flux of gas (F) to the

Table 1. Details of stacks emitting SO_2 at NLC

Stack	Height (m)	SO_2 source strength (g/s)
Thermal Power station-I		
1	60	227.82
2	60	271.35
3	60	153.23
4	120	305.99
Thermal Power station-I Expn.		
1	220	305.07
2	220	305.07
Thermal Power station-II		
1	170	359.38
2	170	359.38
3	170	359.38
4	220	317.45
5	220	317.45
6	220	317.45
7	220	317.45

ground is represented by a first order relationship. Moreover this flux is assumed to be uniform within the surface layer of the atmosphere (10-100 m) (Seinfeld and Pandis, 2006)

$$F = -V_d \times C \tag{1}$$

C is the concentration measured at a reference height within the surface layer. V_d is a parameter called the deposition velocity and it has the units of m/s. Thus the problem of determining the flux of a species is transformed into the determination of its deposition velocity.

2.1. Deposition velocity- Theory of resistances

The process of dry deposition is usually divided into three stages:

1. Transportation from the free atmosphere to the receptor surface (turbulent layer transport)
2. Transport through the quasi-laminar, stagnant air layer near the receptor surface (diffusive molecular transport)
3. Capture or absorption by the surface (in this case transport into the leaf stomata or cuticle or deposition onto the ground).

According to the universally adopted inferential resistance modelling approach, the dry deposition process is treated analogously to the flow of electrical current through a network of resistances in series. In this analogy, the aerodynamic resistance (R_a), the quasi-laminar resistance (R_b) and the surface resistance (R_c) refer to the afore mentioned three stages of dry deposition respectively. The inverse of the total resistance is the dry deposition velocit y (V_d).

$$V_d = \left(R_a + R_b + R_c\right)^{-1} \tag{2}$$

The aerodynamic component of the overall dry deposition resistance is typically based on gradient-transport theory and mass-transfer/momentum-transfer similarity. The resistance varies with the state of stability of the atmosphere. The quasi-laminar resistance depends on the diffusivity of the gas as well as the wind conditions. The aerodynamic and quasi-laminar resistances are computed by the following expressions (Sienfeld and Pandis, 2006).

The quasi-laminar resistance is calculated by the following expression

$$r_a = \begin{cases} \dfrac{1}{\kappa u_*}\left[\ln\left(\dfrac{z}{z_o}\right) + 4.7(\zeta - \zeta_0)\right] & (stable) \\ \dfrac{1}{\kappa u_*}\ln\left(\dfrac{z}{z_o}\right) & (neutral) \\ \dfrac{1}{\kappa u_*}\left[\ln\left(\dfrac{z}{z_o}\right) + \ln\left(\dfrac{(\eta_0{}^2+1)(\eta_0+1)^2}{(\eta_r{}^2+1)(\eta_r+1)^2}\right) + 2\left(\tan^{-1}\eta_r - \tan^{-1}\eta_0\right)\right] & (unstable) \end{cases} \tag{3}$$

Where $\eta_0 = (1-15\zeta_0)^{1/4}$ and $\eta_r = (1-15\zeta_r)^{1/4}$, $\zeta_0 = z_0/L$

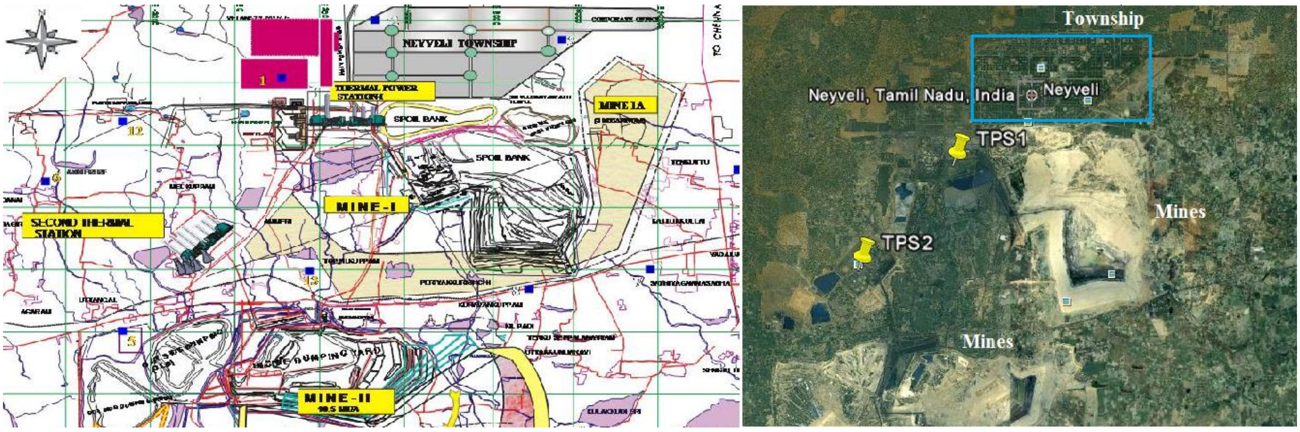

Figure 1. Map of NLC and aerial view from Google Earth® of TPS1 and TPS2 and the Township.

$$R_b = \frac{5Sc^{2/3}}{u_*} \qquad (4)$$

Sc is the Schmidt No; equal to the ratio of kinematic viscosity of air and the binary diffusivity of SO_2 and air. The friction velocity (u_*) can be calculated by

$$u_* = \frac{ku(z)}{\ln\left[(z-d)/z_0\right]}$$

The Monin-Obhukov length (L) which characterizes atmospheric stability was determined from the Pasquill Stability classes by the method of Golder (1972) as detailed in Sienfeld and Pandis (2006). The roughness length (z_0) was taken as 1 m while the displacement length (d) is 70-80% of the roughness elements (Sienfeld and Pandis, 2006). The reference height for this study (z) is taken as 10 m and the von karman constant (k) was taken as 0.4.

The canopy resistance is the most difficult resistance to parameterize due to the complex nature of the processes involved in the absorption and retention of gases by vegetative surfaces. The parameterization of Wesely (1989) is adopted which calculates the canopy resistances by accounting for several sub-resistances in series and parallel (Sienfeld and Pandis, 2006).

$$R_c = \left(\frac{1}{r_{st}+r_m} + \frac{1}{r_{lu}} + \frac{1}{r_{dc}+r_{cl}} + \frac{1}{r_{ac}+r_{gs}} \right)^{-1} \qquad (5)$$

The first term includes the leaf stomatal (r_{st}) and mesophyll (r_m) resistances, the second term is outer surface resistance in the upper canopy (r_{lu}), which includes the leaf cuticular resistance in healthy vegetation and the other outer surface resistances; the third term is the resistance in the lower canopy, which includes the resistance to transfer by buoyant convection (r_{dc}) and the resistance to uptake by leaves, twigs, and other exposed surfaces (r_{cl}) and the fourth term is resistance at the ground, which includes a transfer resistance (r_{ac}) for processes that depend only on canopy height and a resistance for uptake by the soil, leaf litter, and so on at the ground surface (r_{gs}).

Of these the stomatal (rst) resistance is of particular interest since it accounts for the effects of solar radiation and temperature on the opening of the stomata. This has a major effect on the overall resistance and is responsible for day to day variations in the value of the canopy resistance. The bulk canopy stomatal resistance is calculated from tabulated values of r_j (where r_j is the minimum bulk canopy stomatal resistance for water vapor), the solar radiation (G in W/m^2), and surface air temperature (T_s in °C between 0 and 40°C) using

$$r_{st} = r_j \left[1 + \left(\frac{200}{G+0.1} \right)^2 \left(\frac{400}{T_s(40-T_s)} \right) \right] \qquad (6)$$

The seasonal category was kept fixed as mid-summer for all computations due to the evergreen nature of the canopy at NLC. During rains the leaf surfaces become wet, enhancing deposition of SO_2 due to dissolution into the aqueous phase. This effect is incorporated into the model by a suitable reduction in the outer surface resistance in the upper canopy (r_{lu}) (Wesely, 1989). The procedure for calculating the resistances is given in Seinfeld and Pandis (2006).

2.2. Deposition Velocity of SO_2 at NLC

The average deposition velocity of SO_2 is computed for the months of December, May and October which represent the three seasons experienced at NLC- mild winter, hot dry summer and wet North East Monsoon respectively (see Table 2). Calculations were done using data for the months of 2008-09. Recent work by Seth *et al*. (2010) and Patra and Ghosh (2010) present computations of deposition velocities for the NLC region. However these studies do not calculate the aerodynamic resistance via the detailed flux gradient relationships

Table 2. Deposition Velocity for various seasons at NLC

Season	V_d (cm/s)	
	Day	Night
DEC 08- Mild winter	0.487	0.131
MAY 09- Hot Summer	0.443	0.122
OCT 09- NE Monsoon	0.507	0.115

employed in this study nor do they account for the effect of wet leaf surfaces.

Before discussing the seasonal variation in V_d, it is beneficial to understand the factors which influence the deposition velocity by taking a close look at the calculations for the month of December 2008 at 14:30 (daytime). The values of the resistances and V_d computed for each day is shown in Fig. 2. The canopy resistance (R_c) proves to be the controlling resistance in the dry deposition process, accounting for 80% of the total resistance. Hence one would expect the factors which modulate R_c (solar insolation and temperature) to have a marked affect on V_d as well. This is indeed the case. In fact the values of V_d are substantially lower at night since there is no solar radiation and the stomata are practically closed (see Table 2 and Fig. 3).

In order to observe the effect of solar radiation and wind speed on the dry deposition process, the normalized values of R_a and R_c are plotted with the normalized values of wind speed and solar radiation respectively (Fig. 4 and Fig. 5). The clear anti correlation between these factors and the resistances is observable. The variation of R_b with wind speed is much the same as R_a. Fig. 6 shows the variation of V_d with both environmental factors. A close look at day 13 in Fig. 6 makes it clear

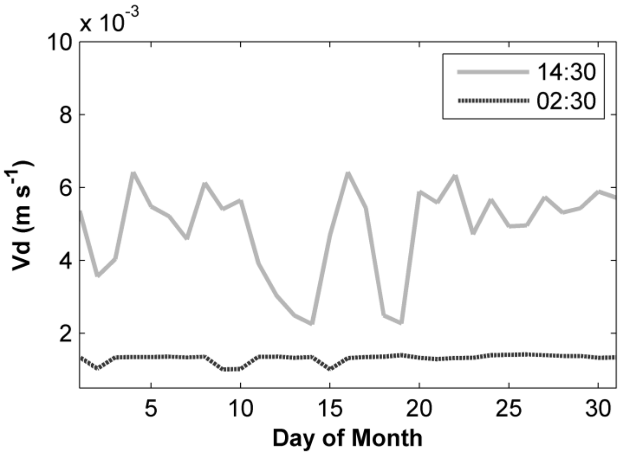

Figure 3. Diurnal variation in deposition velocity for December 2008

that the solar radiation has a stronger role to play than the wind speed. This is because the surface resistance accounts for a major portion of the total resistance.

The seasonal variation in V_d is attributable to the temperature and rainfall since solar radiation is more or less constant through the year. While high solar radiation stimulates stomatal opening and increases dry deposition, high temperatures (close to 40°C) cause the stomata to close. Thus in the month of May, although strong solar radiation is incident, high temperatures above 35°C reduce the value of deposition velocity. During the month of December, the temperature is around 20°C and solar radiation is sufficient for the deposition velocity to be higher than it is in peak summer (May). In October, although the onset of the North East Monsoon would lead to reduced solar insolation, the presence of moisture on the leaf surfaces increases

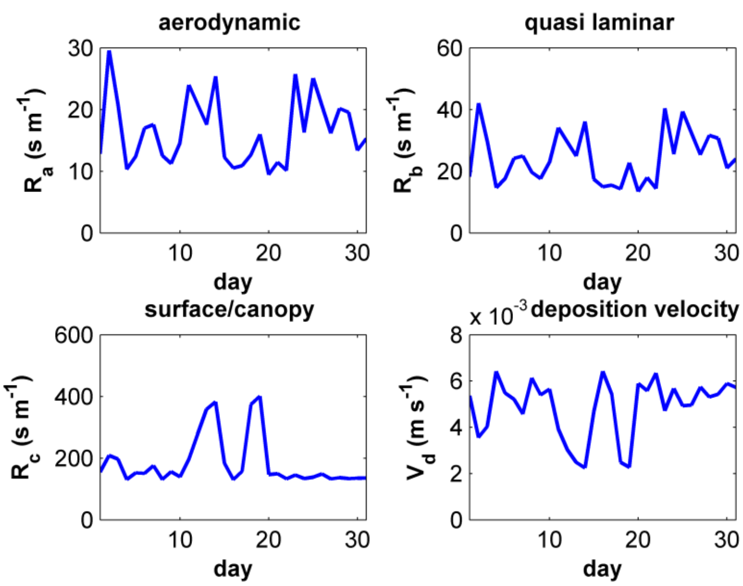

Figure 2. Resistances and deposition velocity calculated for December 2008 at 14:30

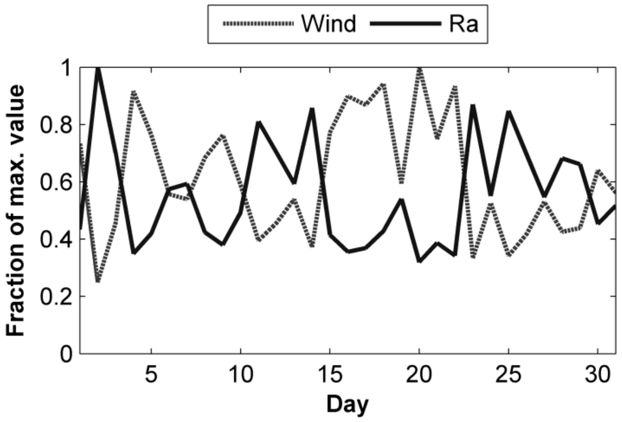

Figure 4. Variation of aerodynamic resistance with wind speed (Dec 2008)

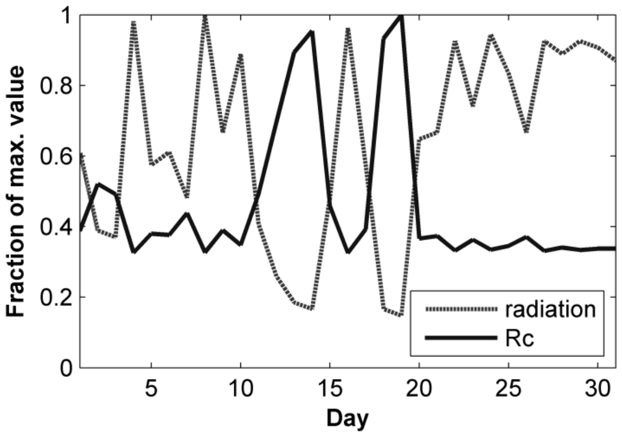

Figure 5. Variation of canopy resistance with solar insolation (Dec 2008)

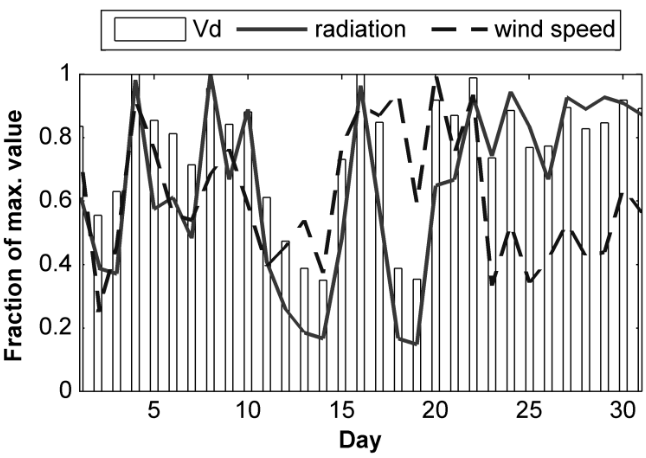

Figure 6. Variation of deposition velocity with wind speed and solar insolation (Dec 2008)

dry deposition due to dissolution of SO_2. We account for this effect using the method proposed by Wesely (1989) and obtain the highest values for V_d during the Monsoon season.

3. Cleansing efficacy of the evergreen canopy

Having calculated values of V_d, it is a simple matter to obtain the flux of species via Eq. (1) if the concentration at the reference height is known (10 m). Measurement of these concentrations for various months of the year is currently in progress. After obtaining this data it will be possible to estimate the total amount of material deposited on the canopy year round. However, this paper is concerned with establishing the efficacy of the cleansing action of the evergreen trees and their role in improving air quality. This is best done by focusing our study on a particular day. On the 13th of May 2009, the wind blew in from the southwest and transported pollution directly over the township. The wind speed was 2 m/s and the solar radiation was 544 W/m^2. In order to obtain the concentration of SO_2 over the township, we apply a tailor made atmospheric gaussian-dispersion model which accounts for the stability of the atmosphere via the Pasquill Stability classes. A detailed exposition of gaussian models can be found in Sienfeld and Pandis (2006) and Hanna *et al*. (1982).

3.1. Deposition from a plume

The emissions from the stacks of TPS1 and TPS2 are driven by the wind over the NLC Township. The ground level concentration computed from the dispersion model is shown in Fig. 7. The township is demarcated by a rectangle; white markers represent the power stations with TPS1 on the edge of the township. The text markers indicate locations of air quality monitoring stations. From Fig. 7 it is clear that much of the township experiences concentrations above 10 μg m^3. Areas closer to TPS1 receive higher amounts of polluting gas and the concentration in the narrow region surrounding the plume centerline exceeds 100 μg/m^3.

Due to the presence of the evergreen canopy, there will be a continuous deposition of material from the plume of pollution onto the trees. This flux will be greater in regions of higher concentration and can be evaluated using Eq. (1). Material will be deposited as long as the plume remains over the canopy and the wind direction holds. However, there will not be any significant change in the ambient air concentration due to deposition, since the source strength is very strong and the township is close to the power station. Nevertheless considerable amount of pollution is deposited

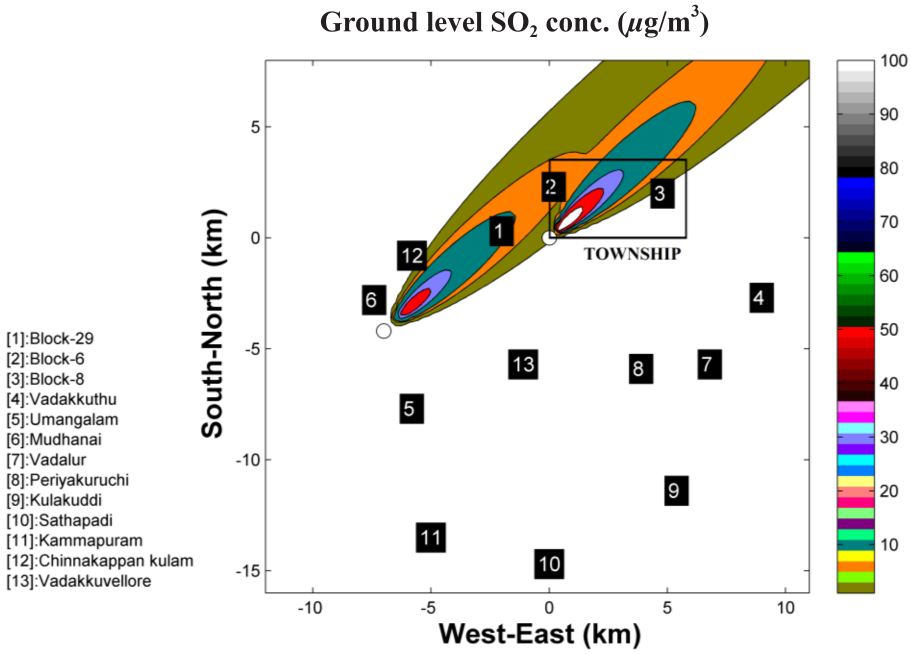

Figure 7. The ground level concentration over the township on 13th May 2009 at 14:30

and contours of the same for an hour are shown in Fig. 8. Totally, 4.5 kg of SO_2 is deposited onto the canopy within the township, in an hour.

Although deposition does not affect the air quality at the township, it will have a beneficial effect on areas surrounding NLC since some amount of the polluting gas has been removed. This study can be generalized for any wind driven plume, over any part of NLC with a canopy cover.

There is another situation in which the trees play an important role. The wind direction will eventually change or a period of sustained wind may be followed by a calm. In either case, pollution will remain hanging over a given area (township in this study) as residual pollution. The following section investigates the role of trees in this scenario.

3.2. Removal of residual pollution and improvement of air quality

The residual pollution left over by a plume will be diluted throughout the mixing layer. The mixing layer

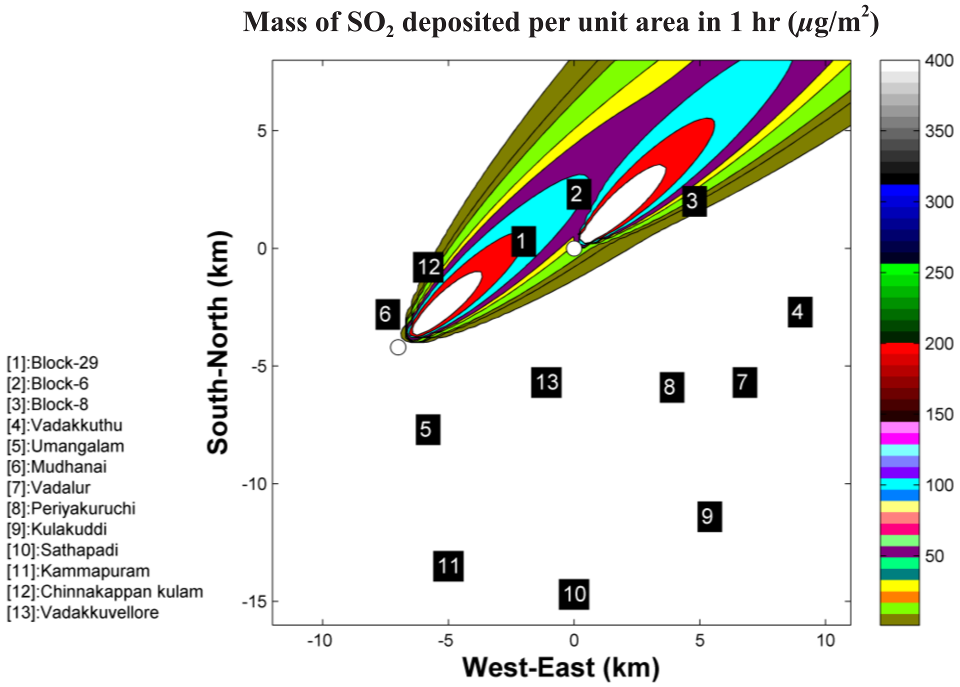

Figure 8. Mass of SO_2 deposited per unit area in 1 hr for the concentration distribution of Fig.7

is the well mixed region of the atmosphere adjacent to the earth's surface. The height of this layer varies with the time of day, the location of the site (latitude) and the atmospheric stability. This pollution will remain hanging over the township until it is advected away by the wind. In such a situation wherein there is no replenishment of pollution from the stack, the trees can play a significant role in air quality improvement. A first order removal of species from the bottom of a closed stirred tank is a simple way of modelling this process. A mass balance on SO_2 for a mixing layer of height Hmix yields:

$$\frac{dC}{dt} = -\frac{V_d C}{H_{mix}} \tag{7}$$

This equation when integrated yields the following expression for the time dependent concentration in the mixed zone of the atmosphere, where C_0 is the initial residual concentration.

$$C(t) = C_0 \exp\left(-\frac{V_d t}{H_{mix}}\right) \tag{8}$$

The initial residual pollutant concentration can be obtained by first estimating the total amount of pollution left over a given area and then distributing it uniformly throughout the mixing layer. This is done by integrating the plume concentration predicted by the dispersion model throughout the atmosphere for all points within a designated zone (say the township).

The above calculation and the application of Eq. (8) to study the removal of residual pollution, requires the estimation of the height of the mixing layer. In this work we make use of the CSIRO mixing height calculator which is based on the work of Luhar (1998). The calculator accounts for both mechanical and convective turbulence and requires input of temperature gradient and latitude apart from other meteorological parameters. Returning to the 13^{th} of May when the atmosphere was unstable, we set the gradient as 0.01°C/m. The temporal variation of the mixing height as calculated is shown in Fig. 9.

From Fig. 9 we see that there is considerable temporal variation in height. A value of 1000 m is on the upper end and is common during summer days. It is lower during winter days and during the night (Seinfeld and Pandis, 2006). For our purpose of demonstrating the cleansing action of trees, we choose two representative values- 1000 m and 500 m. This calculation of mixing height was done to get an estimate of the values which commonly occur during tropical summer conditions at NLC. Thus the above calculation is sufficient despite obvious changes in wind speed and stability which occur during the day.

The reduction in concentration with time due to removal by the canopy over the township is apparent from the application of Eq. (8). Fig. 10 shows the decrease in concentration at both mixing heights. Clearly, the cleansing effect is more pronounced at lower mixing heights.

4. Conclusions

In this study we quantify the removal rates of SO_2 by the evergreen canopy located in a large thermal power plant in South India. It is interesting to compare our results of deposition velocity with those obtained by other modelling and experimental studies. Xu and Carmichael (1998) have employed the methods described in this paper to calculate deposition velocities of SO_2 for the entire Asia region, including South India. However, the spatial resolution of these results is limited. Moreover our calculations consider the meteorological and climatic conditions unique to NLC as well as the effect of wet leaf surfaces. Nevertheless some results are comparable. Their values of V_d (daytime) for May and August are 0.3 and 0.45 respectively. Their value for December is much lower at 0.2 as compared to our result of 0.487. This is due to the mild winter experienced at NLC with optimum temperatures of around 20°C for stomatal opening.

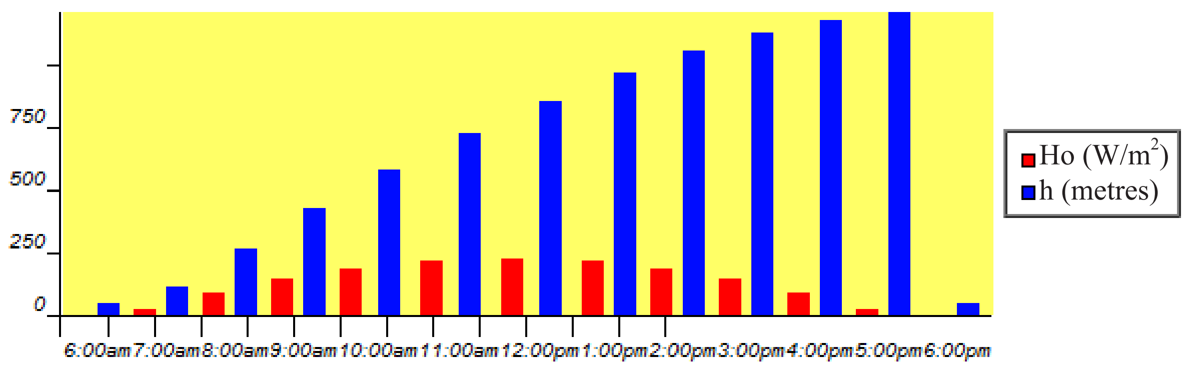

Figure 9. Height of the mixing layer on 13^{th} May 2009

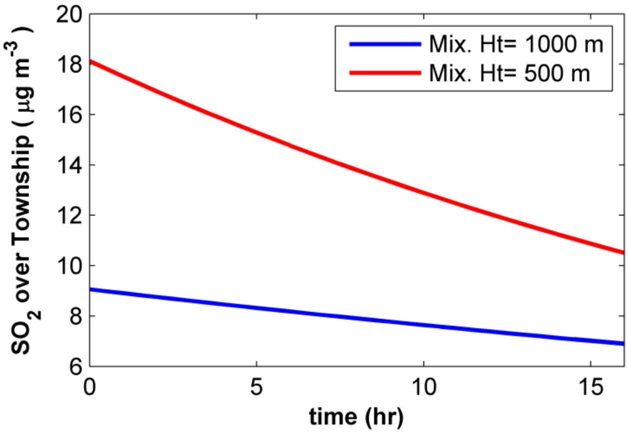

Figure 10. Depletion of residual SO_2 concentration over the township due to removal by trees.

Matsuda *et al*. (2006) performed field experiments to determine the dry deposition velocity of SO_2 over a tropical forest in Northern Thailand. They report values of deposition velocity up to 0.31 cm/s (daytime) and 0.11 cm/s (nighttime) for the dry season. The night time value is nearly the same as our results. Generally the values of V_d (daytime) at NLC are higher, possibly due to year round higher solar insolation. In their work, they describe the importance of accounting for the effect of wet leaf surfaces and the resultant higher values of V_d during the rains.

Having determined the removal rates, we couple this information with an atmospheric dispersion model to investigate the cleansing efficacy of the evergreen canopy. A particular emphasis is placed on the sensitive township which receives the full impact of stack emissions on 13th May 2009. Focusing on this day, we demonstrate the removal of SO_2 from a wind driven plume as well as the removal of residual concentration when the wind direction changes. It is observed that the trees improve air quality in the latter case. This effect is more pronounced at lower mixing heights. During winter days, the mixing layer can be a few hundred meters high and just 100 meters at night due to the formation of an inversion layer. Under such conditions, pollution emitted during the early hours is trapped at night and can result in high levels of pollution. Harmful effects can be mitigated by the presence of trees and their cleansing action. Thus it is especially important to plant trees in urban areas where the major pollution source are located at ground level.

The implications of these results as well as the model developed in this work can be applied to other developing nations of Asia, who are grappling with the problem of air pollution from the burning of fossil fuels. Nature has an ability to absorb and dissipate anthropogenic stresses such as air pollution. These natural mechanisms are pronounced in South Asia where convective boundary layers and evergreen trees are a saving grace. While this is not a green signal to continue polluting the environment, it does emphasize the importance of understanding nature's protective mechanisms and utilizing them to mitigate and control pollution in an economic and sustainable manner.

Acknowledgements

We thank the Neyveli Lignite Corporation (NLC) for funding this work and providing all necessary meteorological data.

References

Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, Surface Flux and Mixing Height Calculator. http://www.cmar.csiro.au/airquality/mixheight/index.html

Hanna SR, Briggs GA, Hosker Jr. RP. Handbook on Atmospheric Diffusion, DOE TIC-11223. Technical Information Center, U.S. Dept. of Energy, USA. 1982; 25-35.

Luhar AK. An analytical slab model for the growth of the coastal thermal internal boundary layer under near-neutral onshore flow conditions. Boundary-Layer Meteorology 1998; 88: 103-20.

Matsuda K, Watanabe I, Wingpud V, Theramongkol P and Ohizumi T. Deposition velocity of O_3 and SO_2 in the dry and wet season above a tropical forest in Northern Thailand. Atmospheric Environment 2006; 40: 7557-64

Patra S and Ghosh S. Quantifying Trace Gas Uptake Rates by Passion Flower Draped Facades and Roofs. Proc. World Green Roof Congress, London, 2010.

Seinfeld JH and Pandis SN. Atmospheric Chemistry and Physics. 2nd ed. John Wiley, New Jersey, USA. 2006; 852-929.

Seth UK, Sarkar S, Bardhan R and Ghosh S. Asia's Largest Lignite based Power Plant's success story: Efficient removal of SO2 through a manmade forest canopy. Proc. WCE, Imperial College, London 2010; 2.

Wesely ML. Parameterization of surface resistance to gaseous dry deposition in regional scale numerical models. Atmospheric Environment 1989; 23: 1293-304

Xu Y and Carmichael G. Modeling the Dry Deposition Velocity of Sulphur Dioxide and Sulphate in Asia. Journal of Applied Meteorology 1998; 37: 1084-99.

Received 4 January 2011
Accepted 19 March 2011

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