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LAGRANGIAN PLUME MODELLING IN THE ATMOSPHERE - MIXING DOWN OF MORNING BUOYANT EMISSIONS

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ABSTRACT

The morning transition period in the atmosphere includes the time from sunrise until early afternoon; it can have drastic effects on plume behaviour and the resultant ground level concentrations of pollutants. Plumes previously emitted into the nocturnal air can then be mixed to the ground by convective actions resulting in high ground level concentrations. Lagrangian particle models can describe plume behaviour during these conditions. Such a model has been developed to predict plume dispersion and pollutant concentration of buoyant source releases. Results from the new model compare favourably to various laboratory experiments representing fumigation due to the break-up of the nocturnal inversion, neutrally buoyant convective releases, convective plume rise, and plume entrapment for a two layer convective/stable atmosphere. The model has been sucessfully applied to various Australian sources such as power stations and mineral extraction plants which emit sulfur dioxide gas.

1.INTRODUCTION

The structure of the model follows that of McNider (1981) and includes a mesoscale model component (CSU model) and a particle model component. The particle model has been rewritten to include updated theoretical developments and turbulence parameterisations. The model theory is based on the general form of the Langevin equation derived by Thomson (1987). The theory used here was formulated by Sawford (personal communication 1988), and has been applied independently to the convective boundary layer in an inhomogeneous skewed form by Luhar and Britter (1989). Section 2 describes the Lagrangian Particle Model (LPM), while Section 3 looks at results from comparisons between the LPM and various laboratory experiments and indicates regions in Australia where the model has been applied.

2.MODEL FORMULATION

Following Sawford (personal communication 1988), the general form of the Langevin equation for the vertical velocity perturbation w' in stationary conditions is

$$dw' = adt + \sqrt{C_0 \epsilon} dW, \qquad (1)$$

where ϵ is the rate of dissipation of turbulent kinetic energy, C_0 is a universal constant, dW is a random variable with a Gaussian distribution (mean 0, variance dt), a is a function of w' and z and is obtained through the solution of

$$\frac{\partial a P_E}{\partial w'} = -\frac{\partial w' P_E}{\partial z} + \frac{1}{2} C_0 \epsilon \frac{\partial^2 P_E}{\partial w'^2}, \qquad (2)$$

where P_E is the probability density function (pdf) associated with the turbulence. The form of a can be determined by integrating the equation for aP_E with respect to w' from $-\infty$ to w', and using the condition $aP_E \to 0$ as $w' \to -\infty$. The first three moments of P_E can be equated to the first three moments of the vertical velocity distribution $\overline{w'} = 0$, $\overline{w'^2} = \sigma_w^2$, and $\overline{w'^3} = S_w^3$.

In convective conditions, we use homogeneous non-Gaussian (skewed) turbulence represented by summing two Gaussian pdf's (one for updrafts and one for downdrafts). With these assumptions a can be derived from the above theory to be of the form

$$a = -\frac{1}{2} C_0 \epsilon \left(\frac{pN_+ (w' - m_+)/\sigma_+^2}{pN_+} \ldots \right)$$

$$\left(\ldots \frac{+(1-p)N_- (w' - m_-)/\sigma_-^2}{+(1-p)N_-} \right), \qquad (3)$$

where p is the probability of being in an updraft, N_+ is a Gaussian pdf for updrafts with mean m_+ and standard deviation σ_+, and N_- is a Gaussian pdf for downdrafts with mean m_- and standard deviation σ_-. Homogeneous turbulence parameterisations used in the model are $\sigma_w = 0.6 w_*$, $Sk = 0.4$, $\epsilon = 0.6 w_*^3 / z_i$, and $C_0 = 2.0$, where σ_w is the standard deviation and $Sk = (S_w/\sigma_w)^3$ is the skewness of the vertical velocity pdf, w_* is the convective velocity scale and z_i is the mixed layer height.

In stable conditions, we use inhomogeneous Gaussian turbulence for which a takes the form

$$a = -\frac{C_0 \epsilon w'}{2\sigma_w^2} + \sigma_w \frac{\partial \sigma_w}{\partial z} \left(1 + \left(\frac{w'}{\sigma_w} \right)^2 \right). \qquad (4)$$

Turbulence parameterisations were based on those of Yamada (1983). With our scheme, calculation of the turbulent kinetic energy (TKE) is diagnostic, depending only on the mean variables predicted by the mesoscale model. The turbulence has vertical gradients using this approach, which necessitates the use of the inhomogeneous Langevin equation.

Plume rise is accounted for by numerically solving the Briggs (1975) ordinary differential equations to determine the mean plume rise velocity. Termination of plume rise occurs when the buoyancy of a particle decreases to be less than zero or when the plume dissipation rate decreases to be less than the ambient dissipation rate. The mean plume rise velocity is added to the vertical velocity of each particle. To account for the turbulence generated by plume buoyancy and momentum effects, the form of a is modified by adding an extra Gaussian pdf with mean zero and standard deviation proportional to the mean plume velocity. The eddy dissipation used in the Langevin equation must be modified to represent the total turbulence as the sum of ambient and plume components. In Gaussian turbulence a simplification is possible, which allows the normal Langevin equation to be used with summed variances and eddy dissipations.

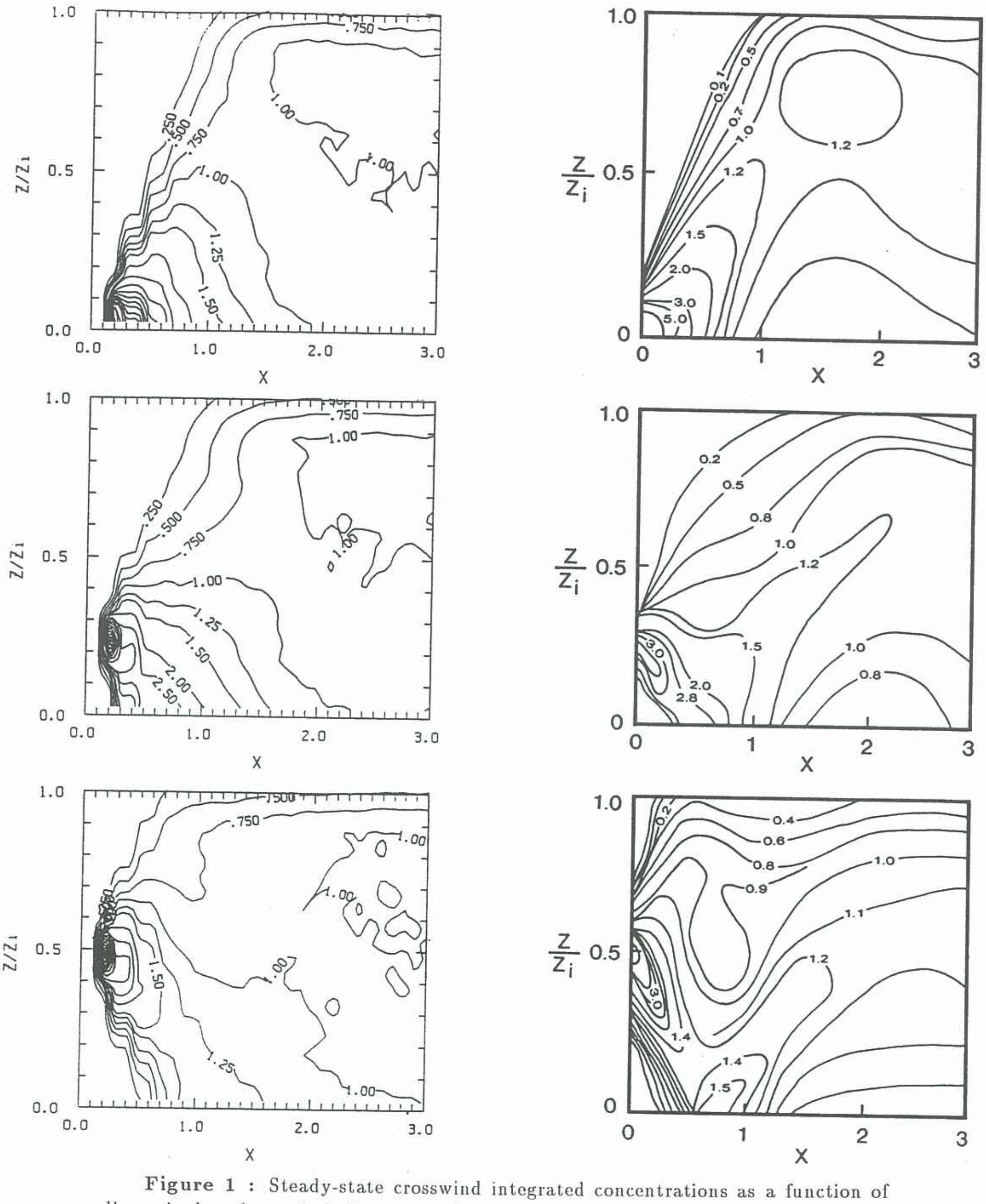

Figure 1 : Steady-state crosswind integrated concentrations as a function of dimensionless downwind distance predicted by the LPM (left) and measured in the laboratory (right) for various source heights.

3.MODEL VALIDATION AND APPLICATION

Hurley and Physick (1991) presented results for nocturnal inversion break-up fumigation which showed that the LPM agreed with an empirical model based on the results of the Deardorff and Willis fumigation experiments - the Modified Deardorff and Willis Fumigation Model (MDWFM). The empirical model was fitted to their laboratory experiments and was modified to account for the effects of a finite plume depth. The LPM predicted both the magnitude and timing of fumigation within the experimental errors. In fact the paper concluded that a simple Gaussian homogeneous form of the model predicted hourly average ground level concentrations just as well as more complex models.

In the laboratory, Willis and Deardorff (1976, 1978, 1981) examined vertical dispersion in convective conditions by releasing non-buoyant particles at heights of z_s/z_i = 0.067, 0.24, and 0.49. Hurley and Physick (1992) modelled these laboratory experiments using the LPM described above and showed that the model reproduces the observed pattern of plume descent to the ground within $X = (xw_*/uz_i) < 1$ from the source, where u is the wind speed (Figure 1). However, the plume lift-off behaviour seen in the laboratory experiments was not simulated, indicating that it may arise from the inhomogeneity of the turbulence. Model predictions of maximum ground level concentration and the downwind distance to this maximum compared well with the laboratory experiments.

Willis and Deardorff (1983, 1987) conducted water tank experiments with a convective mixed layer topped by a stable layer and obtained plume rise and entrapment results for various values of the scaled plume buoyancy flux F_*. They defined the entrapment of a fraction of a plume by the mass of the plume above $0.8z_i$ scaled by the mass of the equivalent plume with no buoyancy. Hurley and Physick (1993) showed that results from the LPM compared well against the results of the laboratory experiments (Figure 2). The entrapment results were very sensitive to the mean plume rise, and it was found that the peak entrapment values were predicted well when the plume entrainment coefficient was slightly larger in convective conditions than in stable conditions.

The LPM described above and the CSIRO Division of Atmospheric Research's model LADM, which consists of the LPM and an in-house developed mesoscale windfield model, have been used and validated for numerous locations throughout Australia. Locations include : the Yallourn group of power stations in the Latrobe Valley Victoria; Collie, Hill River and Pinjar power stations in Western Australia; Kalgoorlie Consolidated Gold Mines in Western Australia; Westralian Sands Synthetic Rutile Plant in Western Australia; Gladstone power station and various industries in Queensland; and by Physick et al. (1992) for the NSW Hunter Valley and Central Coast power stations.

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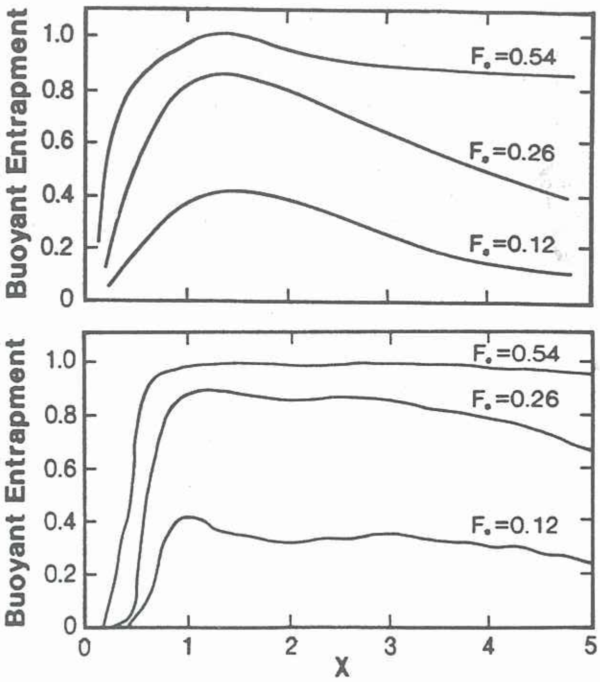

Figure 2 : Plume Entrapment as a function of dimensionless downwind distance predicted by the LPM (bottom) and measured in the laboratory (top) for various values of scaled plume buoyancy (F_*).

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