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STUDIES OF FUMIGATION PROCESSES IN ATMOSPHERIC THERMAL INTERNAL BOUNDARY LAYERS

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ABSTRACT

Fumigation in coastal areas is a turbulent dispersion process. It involves the entrainment into a spatially growing thermal internal boundary layer (TIBL) of a plume of pollutants released from a tall stack within the (normally stable) layer above. The plume is subsequently mixed in the TIBL by the convective turbulence. Fumigation models are often employed in air quality management to determine pollutant concentrations in the TIBL. In this paper, we compare fumigation models of varying complexity for typical values of entrainment rate and plume spread at the plume-TIBL interface. It is observed that, when compared with the results from a physically more realistic Lagrangian stochastic model, existing analytical models that assume uniform and instantaneous vertical mixing in the TIBL give inaccurate results when the entrainment rate is large and/or the vertical plume spread small at the interface. We present a new fumigation model based on a probability density function (PDF) approach. The PDF model is capable of better representing the fumigation process than existing analytical models. Experimental work undertaken by the CSIRO Division of Atmospheric Research (DAR) on fumigation is briefly described.

INTRODUCTION

In a shoreline environment, the water is usually colder than the air during the day, thus generating a stable air mass over the water. A thermal internal boundary layer (TIBL) forms over land when the stably stratified air flows from water onto warmer land. The TIBL is a convective boundary layer (CBL) which grows with distance inland. A contaminant plume released from a tall stack (i.e. a point source) in the stable region above the TIBL moves inland with very little vertical diffusion. Eventually, at a downwind distance that is determined by the effective source height and the boundary layer growth rate, the plume intersects the TIBL and is rapidly dispersed downwards to the ground by the convective turbulence; this phenomenon is known as coastal or shoreline fumigation (Fig. 1). The fumigation process may persist for many hours, and may lead to high ground-level concentrations (GLCs) of pollutants. The study of fumigation is of considerable practical importance since many potentially polluting installations are located in coastal zones. In this work, our main emphasis is on the mathematical modelling of this transport process to calculate pollutant concentrations.

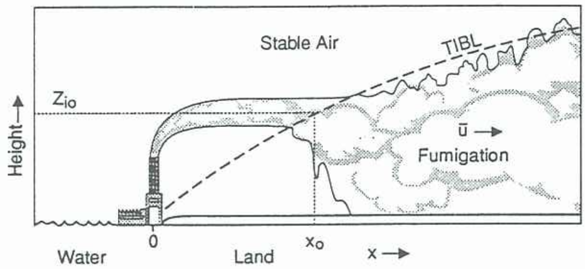

FIG. 1: Illustration of the coastal fumigation phenomenon. The TIBL is shown by the dashed line.

THERMAL INTERNAL BOUNDARY LAYER

Determination of the TIBL height is an important component of coastal dispersion models because the point at which TIBL intercepts the plume influences the distribution of GLCs. The TIBL is essentially a growing CBL. Its height (z_i) is generally given as (e.g. Stunder and Sethu-Raman, 1985):

$$z_i = A_o x^{1/2} \tag{1}$$

where x is the inland distance from the land-water interface, and A_o is a function of meteorological and physical parameters. The value of A_o is used as an input to determine the plume-TIBL interface location.

Similar to the mixed-layer scaling applied in CBL studies, the nondimensional downwind distance in the TIBL is taken as:

$$X = \frac{x\, w_*}{z_{io}\, \overline{u}}, \tag{2}$$

where $\overline{u}$ is the mean wind speed in the TIBL, z_{io} is the height where the TIBL intercepts the plume-centreline (therefore, z_{io} is essentially the effective source height or the plume equilibrium height), and w_* is the convective velocity. The height (z) and crosswind (y) coordinates are scaled with z_{io}.

We define the entrainment rate (w_e) as the growth rate of the TIBL. The nondimensional entrainment rate at the

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point of interception of the plume-centreline and the TIBL is given as:

$$\frac{w_{eo}}{w_*} = \frac{\overline{u} A_o^2}{2 w_* z_{io}} = \frac{1}{2 X_o}, \qquad (3)$$

where X_o is the nondimensional downwind distance at which $z_i = z_{io}$. The nondimensional growth of the TIBL can be expressed as:

$$\frac{z_i}{z_{io}} = \left(\frac{X}{X_o}\right)^{1/2}. \qquad (4)$$

MODELLING SHORELINE FUMIGATION

Several analytical point-source fumigation models are currently in use for predicting GLCs of airborne materials from tall stacks. Perhaps the most serious problem with most models (e.g. Misra, 1980) is the assumption that a plume mixes instantaneously and/or uniformly in the vertical immediately after it has encountered the TIBL. Under certain conditions (discussed later), this assumption leads to inaccurate prediction of GLC variation with downwind distance. Also, no allowance is made in these models to account for the inhomogeneity and skewness of the vertical convective turbulence in the TIBL which are known to affect plume dispersion significantly, e.g. the existence of counter-gradient fluxes.

The above model shortcomings can be overcome by following the Lagrangian stochastic approach. A model based on this method describes atmospheric dispersion of a scalar in terms of random motion of fluid elements or particles. Using the mean and turbulence properties of a flow, thousands of particle trajectories are calculated, each corresponding to a different flow realization, to derive the ensemble-average concentration distribution. Such models have several advantages over Eulerian advection-diffusion models and are capable of realistically simulating dispersion even in complex flows, such as a CBL (see, for example, Sawford and Guest 1987).

Luhar and Britter (1990) applied a one-dimensional (1-D) stochastic dispersion model to coastal fumigation. Many passive particles were released at the plume-TIBL interface with given spreads. The motions of the particles were calculated within the TIBL and concentrations were estimated by counting the number of particles in small cells. This model, which was an extension of their earlier model (Luhar and Britter, 1989) developed to simulate vertical dispersion in the CBL, accounted for the variation of the TIBL height with distance and used Taylor's translation hypothesis to relate travel times to downwind distances through the use of wind speed. Luhar and Sawford (1995a) developed a 2-D stochastic model incorporating the diffusion and gradients (i.e. derivatives) of flow properties in both the vertical and horizontal directions in the TIBL. The model results showed that in most cases the omission of diffusion and the gradients of flow properties in the streamwise direction does not influence the dispersion significantly, and that the 1-D stochastic model is adequate for describing the fumigation process. This 1-D model performed well when compared with fumigation observations. The main shortcoming of Lagrangian stochastic models, however, is that they require large computational resources and, therefore, are often not suitable for routine calculations.

We have developed an analytical fumigation model based on a probability density function (PDF) approach for routine calculations which can satisfactorily account for a realistic vertical mixing process in the TIBL (see Luhar and Sawford, 1995b, for details). This model is much faster than the above stochastic models. It assumes that particles released at the source height with velocities equal to the Eulerian turbulent velocities travel in straight line trajectories until they approach the top or the bottom of the boundary layer. This is a reasonable assumption since the Lagrangian time scale in the CBL (and hence in the TIBL) is generally large. A perfect reflection scheme is used at the boundaries. The model calculates concentration (mass per unit volume) at any point in the TIBL as:

$$\overline{c}(x,y,z) = \frac{Q}{2\pi} \int_0^x \frac{1}{(x-x')\,\sigma'} \exp\left[-\frac{s^2}{2} - \frac{y^2}{2\,\sigma'^2}\right] \times \left\{\sum P_w[w(z)]\right\} \frac{ds}{dx'}\, dx', \qquad (5)$$

where y is the lateral (i.e. crosswind) distance, z the height, Q the point source strength (mass per unit time), $\sigma'(x,x')$ the lateral diffusion coefficient of the plume within the TIBL, $s = [z_i(x') - z_{io}]/\sigma_{zs}(x')$, z_{io} the effective source height, and σ_{zs} the vertical dispersion coefficient in the stable layer.

The skewed PDF $P_w[w(z)]$ of vertical turbulent velocities in the convective turbulence is given as:

$$P_w[w(z)] = 0.4\, P_A(w,z) + 0.6\, P_B(w,z), \qquad (6)$$

where $P_A = (\sqrt{2\pi}\,\sigma_A)^{-1} \exp(-0.5[(w - \overline{w}_A)/\sigma_A]^2)$ and $P_B = (\sqrt{2\pi}\,\sigma_B)^{-1} \exp(-0.5[(w + \overline{w}_B)/\sigma_B]^2)$. The PDF P_A corresponds to velocities in updrafts while P_B to those in downdrafts. $\overline{w}_A = 0.45 w_*$, $\overline{w}_B = 0.30 w_*$, $\sigma_A = 0.58 \overline{w}_A$, and $\sigma_B = 0.58 \overline{w}_B$. The vertical velocity $w(z) = [\overline{u}/(x - x')][\pm z - z_i(x') + 2N z_i(x)]$. N is any integer (i.e., 0, ± 1, ± 2, ...). The summation in equation (5) is over N twice corresponding to $\pm z$. It accounts for the reflection of contaminant particles at the boundaries. For calculating the GLC (i.e., at $z = 0$), the term ± 0 in the expression of $w(z)$ must be considered (instead of just 0). A value of $|N|$ in the range of 4–6 is sufficient for convergence of the series. Some of the parameters in the PDF model have been estimated using the 1-D stochastic model of Luhar and Britter (1989) for convective conditions.

A comparison of our new PDF model results with those obtained using Misra's (1980) often-used simple fumigation model and the 1-D stochastic model of Luhar and Sawford (1995a) is made in the next section. The models were run for a typical nondimensional entrainment rate of $w_{eo}/w_* = 0.1$ which would occur when, for example, $A_o = 4.30$ m$^{1/2}$, $\overline{u} = 5.1$ m s^{-1}, $w_* = 1.3$ m s^{-1}, $z_{io} = 363$ m. Plume diffusion in the stable boundary layer can be determined relatively easily using simple methods, such as Gaussian plume models. We consider, for simplicity, a single continuous point source located at the land-water interface (i.e., $x = 0$). We assume that the final plume rise is reached prior to the interception by the TIBL so the dispersion within the TIBL is essentially that of passive material.

Fumigation models mainly differ in their treatment of diffusion in the vertical direction. To examine the vertical diffusion component, independent of the lateral diffusion, we look at the behaviour of the nondimensional ground-level crosswind-integrated concentration $\overline{C^y}(X,0) [= \overline{c^y}(x,0)\, \overline{u}\, z_{io}/Q]$ as a function of X, where X is given by equation (2) and $\overline{c^y} (= \int_{-\infty}^{\infty} \overline{c}\, dy)$ is the dimensional crosswind-integrated concentration (mass per unit area). Two initial plume diffusion conditions are considered: (A) $\sigma_{zo}/z_{io} = 0.05$ (narrow plume), and (B) $\sigma_{zo}/z_{io} = 0.25$ (wide plume). The parameter σ_{zo}/z_{io} is the vertical diffusion coefficient in the stable layer at the location where the TIBL intercepts the plume-centreline (i.e.

$X = X_o = 5$). Based on the behaviour of buoyant plumes from tall stacks in the stable boundary layer, σ_{zs} is taken to be constant with x when the final plume rise is reached prior to the interception of the plume by the TIBL (Misra, 1980). In our stochastic model, many passive particles are released at the plume-TIBL interface with the (Gaussian) spread equal to σ_{zo}.

COMPARISON OF MODELS

Figure 2 presents contours of $\overline{C^y}$ for the narrow initial plume case ($\sigma_{zo}/z_{io} = 0.05$) determined using the three models. The dashed lines in these plots represent the nondimensional TIBL height variation as determined from equation (4). Misra's (1980) model assumes a uniform and instantaneous mixing which is reflected in Fig. 2a. This model predicts a peak ground-level $\overline{C^y}$ value of about 0.9 at $X \approx 6.0$. The stochastic model gives a more realistic dispersion pattern (Fig. 2b); the plume takes a finite time to be brought down to the ground by the convective turbulence and the mixing is nonuniform. At the ground, it predicts a peak $\overline{C^y}$ value of 1.2 at $X \approx 8.0$, which is about 30% larger than that predicted by the model in Fig. 2a. The $\overline{C^y}$ contours in Fig. 2c determined by the new PDF model of Luhar and Sawford (1995b) closely resemble those obtained using the stochastic model. At large distances ($X > 14$), all models predict a near uniform concentration distribution in the vertical as the plume becomes uniformly mixed in the TIBL due to ambient turbulence. The $\overline{C^y}$ variation at such distances is almost equal to $(X_o/X)^{1/2}$.

Figure 3 shows corresponding contour plots for the wide initial plume ($\sigma_{zo}/z_{io} = 0.25$). The qualitative features of diffusion in this case are the same as in Fig. 2. However, the diffusion occurs over a much wider scale with a slower GLC variation with X than shown in Fig. 2. In Fig. 3a, the maximum GLC occurs at $X \approx 8.5$ with a value of about 0.7. The stochastic and PDF models give the same peak value at $X = 9.5$ (Figs. 3b and 3c). Although the entrainment rates are the same in Figs. 2 and 3, the locations of the maximum GLCs are different; this difference is attributed to the asymmetry of diffusion within the TIBL.

The PDF model is computationally more efficient than the stochastic model. For the present runs, it was over 100 times faster.

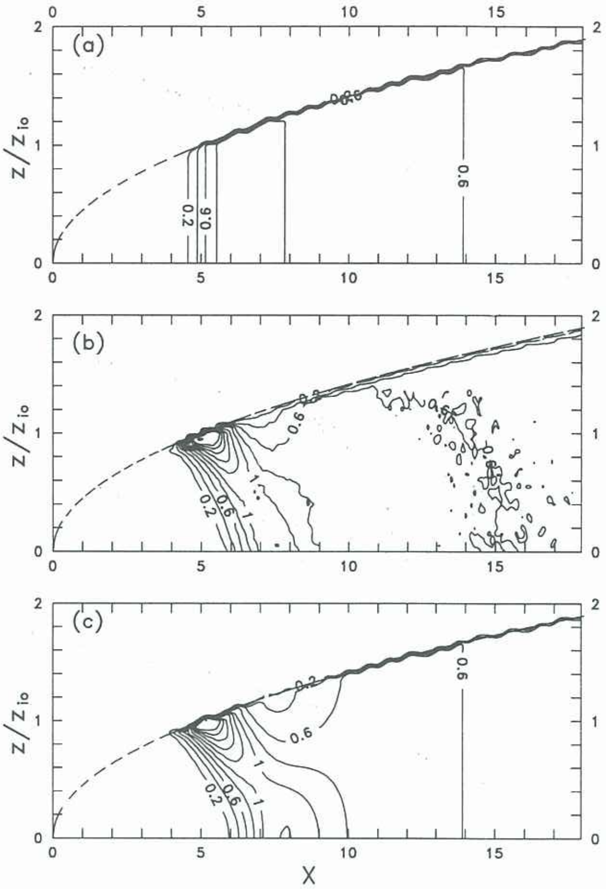

FIG. 2: Contours of the dimensionless crosswind integrated concentration ($\overline{C^y}$) as functions of the dimensionless downwind distance (X) and the dimensionless height z/z_{io}, predicted for the nondimensional entrainment rate $w_{eo}/w_* = 0.1$ and the nondimensional vertical plume spread $\sigma_{zo}/z_{io} = 0.05$ using (a) Misra's (1980) model, (b) Luhar and Sawford's (1995a) Lagrangian stochastic model, and (c) the new PDF model of Luhar and Sawford (1995b). The dimensionless TIBL height is shown by a dashed line. The contour levels are 0.2–2 with a spacing of 0.2.

EXPERIMENTAL WORK

Figures 2 and 3 show that when the vertical plume spread at the plume-TIBL interface is larger, the differences between model predictions become smaller. This is also the case when the entrainment rate is slower (no plots shown). Luhar and Sawford (1995a) applied the stochastic model to the data from the Nanticoke Fumigation experiment conducted in 1978 in Ontario, Canada (Portelli, 1982), and to the water tank data of Deardorff and Willis (1982) and found good agreement. However, it was observed that good agreement could be obtained with Misra's simple model also, since the initial plume spread in the former data set was large (due to the coalescence of plumes from two stacks) while the entrainment rates in the latter were small. Other deficiencies of the Nanticoke data set for modelling purposes included the lack of source emission data and the absence of concentration measurements within the initial mix-down region. The above data sets may not be typical of many field situations involving single plumes. The CSIRO Division of Atmospheric Research (DAR) has undertaken fumigation experiments in the laboratory and the atmosphere to investigate the fumigation process under a wider rage of entrainment rate and initial plume spread conditions. A brief introduction to these experiment is given below.

Laboratory Experiments

The convective water tank facility at DAR is being used to study fumigation (Hibberd and Sawford, 1994; Hibberd and Luhar, 1995). In this tank, a convective boundary layer (CBL) grows with time and there is no mean flow. A fumigant ribbon initially lying above the CBL in a stable environment is intercepted by this boundary layer at a particular time, resulting in fumigation. The results are applicable to the shoreline fumigation using Taylor's translation hypothesis.

Field Experiment

A major field experiment on fumigation was organized by DAR near the coastal industrial region of Kwinana, Western Australia, during January-February, 1995. The other organisations that participated in the experiment were CSIRO's Division of Coal and Energy Technology, Flinders University, Department of Environmental Protection of Western Australia, SECWA, and Murdoch University. Sea-breeze fumigation of plumes from the SECWA

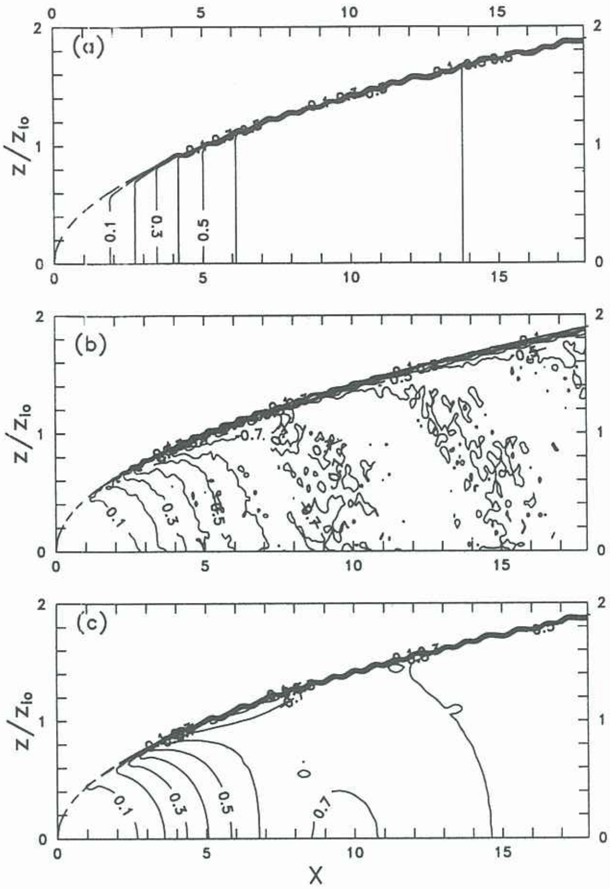

FIG. 3: Same as Fig. 2 but with the nondimensional vertical plume spread $\sigma_{zo}/z_{io} = 0.25$. The contour levels are 0.1–1 with a spacing of 0.1.

power plant into TIBLs formed overland was studied using an instrumented aircraft, radiosonde balloons, meteorological towers, a lidar, a mobile surface sampler, and a sonic anemometer. The experiment provided a complete fumigation data set comprising high quality concurrent measurements of emission, meteorological, and concentration data with which models can be tested.

We are currently analyzing data from this experiment and hope to include some results during the conference presentation.

CONCLUSIONS AND FUTURE WORK

In coastal areas, fumigation over land occurs frequently in daytime during onshore flows. In this paper, we have compared fumigation models of varying complexity for typical values of entrainment rate and plume spread at the plume-TIBL interface. It was found that, when compared with the results from a Lagrangian stochastic model, existing analytical models (e.g. Misra, 1980) that assume uniform and instantaneous vertical mixing in the TIBL, give inaccurate results for large entrainment rate and/or small vertical plume spread at the interface. A new fumigation model based on a probability density function (PDF) approach has been presented. The PDF model is capable of better representing the fumigation process than existing analytical models.

Deardorff and Willis (1982) argued that the growth of the mixed layer in fumigation studies cannot be assumed to be smooth and that the effects of the vertical variability (Δz_i) in the local TIBL height (z_i) are important. Work is currently underway to investigate this variability in our tank experiments and to include it in the new PDF model (Hibberd and Luhar, 1995). The inclusion of the variability tends to flatten the concentration variation with downwind distance, reducing the magnitude of the maximum GLC and moving its location further downwind.

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