DOWNWIND NON-UNIFORM MIXING IN SHORELINE FUMIGATION PROCESSES

(*Research Note*)

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Abstract. The assumption of vertical uniform mixing in shoreline fumigation models is tested using two types of modifications to a base statistical model that takes into account non-uniform mixing. One of the modifications involves the use of a downdraft velocity scheme developed for a convective boundary layer. The other modification is based on an empirical adjustment factor derived from water tank experiments. Results from all three models are compared with field observations. Comparisons indicate that the modifications do not improve the results of the base dispersion model.

1. Introduction

Dispersion modeling in coastal areas where a land-water surface discontinuity plays a major role must take into account a parabolic shaped Thermal Internal Boundary Layer (TIBL) that develops under onshore flow conditions. The TIBL has been shown (Lyons, 1977; Stunder and SethuRaman, 1985) to affect significantly the determination of ground-level concentrations from coastal sources.

Plumes initially emitted into the stable marine air above the TIBL are entrained into the TIBL upon intersecting the growing TIBL interface and consequently fumigate downward. This phenomena is shown in Figure 1. The coastal dispersion modeler is therefore faced with two crucial questions: (1) What is the height and structure of the TIBL? and (2) Is the plume instantaneously mixed downward upon TIBL impaction? Answers to the first question were addressed recently by Stunder and SethuRaman (1985) based on an analysis and evaluation of the various TIBL prediction equations.

Early coastal dispersion modeling efforts (Lyons and Cole, 1973) assumed that the plume is immediately mixed to the ground-level on impaction with the TIBL. Several coastal dispersion models developed in the late 1970's and early 1980's (Van dop *et al.*, 1979; Misra, 1980; Cole and Fowler, 1982) have also assumed instantaneous mixing.

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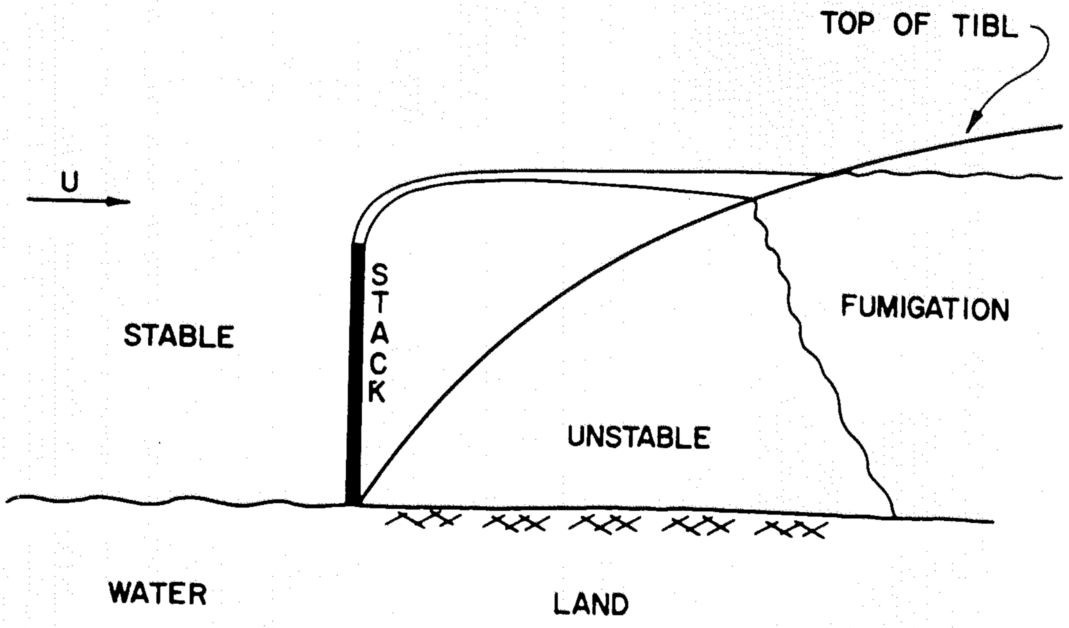

Fig. 1. Typical plume dispersion in a coastal area.

But intuitively one would expect the elevated plume to mix into the TIBL gradually. It has been shown empirically by Deardorff and Willis (1982) based on a laboratory experiment that the location of maximum ground-level concentration is a function of the shape of the distribution of the material in the vertical and that the plume may not become well mixed at the location of its intersection with the TIBL. Another approach to account for gradual diffusion is to model statistically the mixing in the TIBL based on downdrafts in the layer in a manner similar to that suggested by Misra (1981) for a convective boundary layer.

In this paper we incorporate the laboratory empirical scheme of Deardorff and Willis (1982) and the modified statistical downdraft scheme of Misra (1981) into a base coastal dispersion model developed by Misra (1980). The results from the three schemes (the model assuming instantaneous mixing, the model modified to account for downdrafts and the laboratory empirical formulation) are compared with observational data.

2. The Models

2.1. BASE MODEL

The coastal dispersion model of Misra (1980) was chosen as the base model. This model assumes that dispersion of pollutants in the stable layer and within the TIBL proceed independently. Dispersion into the TIBL is assumed to occur from an elevated areal source coincident with the intersection of the plume and the TIBL.

With two further assumptions that transport of the plume into the TIBL occurs by the entrainment of the pollutants due to downwind increase of TIBL height, h, and that the diffusion into the TIBL is by dispersion processes in the stable layer, Misra (1980) expressed the net flux $F(x, y)$ through the top surface of the TIBL as

$$F(x, y) = C_s(x, y, h)\left\{U_s \frac{\mathrm{d}h}{\mathrm{d}x} + \frac{K_{z_s}}{C_s}\frac{\mathrm{d}C_s}{\mathrm{d}z}\right\} \tag{1}$$

where
U_s = the wind speed in the stable layer at height h (m s^{-1})
K_{z_s} = the vertical eddy diffusivity coefficient in the stable layer,
C_s = the concentration on the stable layer (ppb)
h = TIBL height (m).

Using this as a source strength at each point, x', y', on the TIBL top surface and assuming a Gaussian cross-wind distribution and uniform vertical distribution in the TIBL, Misra (1980) obtained a ground-level concentration distribution as below:

$$C(x, y) = \frac{Q}{2\pi h(x)} \int_0^x \frac{1}{U_m \sigma'} \exp\left\{-\left(\frac{h(x') - H_e(x')}{\sqrt{2}\,\sigma_{z,s}(x')}\right)^2 - \frac{y^2}{2\sigma'^2}\right\} \cdot \frac{\mathrm{d}}{\mathrm{d}x'}\left\{\frac{h(x') - H_e(x')}{\sigma_{z,s}(x')}\right\} \mathrm{d}x' \tag{2}$$

where
Q = emission rate (g s^{-1})
U_m = wind speed in the TIBL (m s^{-1})
H_{e_2} = effective stack height (m)
σ' = sum of cross-wind diffusion values in the stable layer $(\sigma_{ys})^2$ and the TIBL (σ^2_{yh}) (m).

Standard deviations, $\sigma_{y,s}$, $\sigma_{z,s}$, and $\sigma_{y,h}$ were parameterized with appropriate variables (see Misra, 1980, for details).

2.2 MODIFICATION OF THE BASE MODEL FOR DOWNDRAFTS OCCURING IN THE TIBL

Misra (1981) has shown that within a convective boundary layer, the turbulence is characterized by 'updrafts' and 'downdrafts' which are essentially large eddies scaling with boundary-layer depth.

Although the entrainment at the top of the TIBL is dominated by the characteristics of the interfacial layer (Wyngaard, 1984), it is plausible that the entrained material is carried to ground-level by the downdrafts. It is then possible to use the method developed in Misra (1981) to delineate the vertical distribution inside the TIBL.

We assume that the elemental area source as described in Misra (1980) has a height equal to the TIBL height at that location. Since the material can mix into the TIBL from this location only when it is caught in downdrafts, we shall ignore the effects of updrafts. Here we assume that a downdraft has a sufficient lifetime such that materials emitted into it remain inside until they touch down at ground level.

The reader is referred to Misra (1981) for details of the distribution function inside a convective boundary layer. Here we shall use this function by making the following assumptions:

$$\begin{aligned} f_1(z) &= -(z/h)^{1/3}(1 - 1.1z/h); & 0.025 \leqslant z/h \leqslant 0.675 \\ &= -0.225; & 0.675 \leqslant z/h \leqslant 1 \end{aligned} \tag{3}$$

where $f_1(z)$ is the functional representation of the variation of downdraft velocity with height.

It is assumed that the velocity with which the material is injected into the downdrafts is a constant in the upper 1/3 of the boundary layer. It is also assumed that the standard deviation of the vertical velocity can be written as:

$$\sigma_{w_d}^2 = 2.4 w_*^2 (z/h)^{2/3} \{1 - 0.77(z/h)^{1/4}\}^2 \tag{4}$$

where

σ_{w_d} = standard deviation of vertical velocity and

w_* = convective velocity scale.

We define a function $g(z)$ as follows:

$$g(z) = -\int_h^z \frac{\mathrm{d}z}{f'(z)} . \tag{5}$$

When used for computing the ground-level concentration, the upper limit in the integral of Equation (5) is set equal to 0.0258. This gives the $g(0.0258)$ equal to $3 \cdot 1h$. The reader is referred to Willis and Deardorff (1978) for an explanation of setting the lower boundary at $0.025h$.

With the above definition, the expression for the ground-level concentration inside the TIBL (Equation (2)) is replaced by the following:

$$C/Q = \frac{1.78}{2\pi w_*} \int_0^x \frac{\sigma'^{-1}}{(x - x')} \exp\left[-\left(\frac{h - H_e}{\sqrt{2}\,\sigma_z}\right)^2 - \left\{\frac{1.74Uh}{w_*(x - x')} - 0.198\right\}^2 \right.$$

$$\left. - y^2/2\sigma'^2 \right] \mathrm{d}/\mathrm{d}x' \left(\frac{h - H_e}{\sigma_z}\right) \mathrm{d}x' . \tag{6}$$

Here σ_z is the dispersion parameter in the stable layer and σ' is the same as defined by Misra (1980). However, when $(x - x') > 4hU/w_*$, one may use the expression with uniform vertical mixing. This assumption is based on the experimental results of Willis and Deardorff (1978) where uniform vertical mixing was observed for a non-dimensional distance $w_* x/hU > 4$.

It is noted that the above expression is valid for $(x - x') > 0$. However, when $(x - x') \geqslant 4hU/W_*$, one may use the expression with uniform vertical mixing. This will make the computation more efficient.

2.3. MODIFICATION BASED ON AN EMPIRICAL FORMULATION OBTAINED FROM PHYSICAL MODELING

Deardorff and Willis (1982) suggest an empirical adjustment to account for the delay in touchdown at ground-level of the pollutants entrained at the top of the TIBL. Their empirical adjustment factor is based on water tank experiments where depths of stable and mixed-layers were physically modelled. The adjustment factor K is given in terms of dimensionless quantities as:

$$\begin{aligned} K &= 3T''^2 - 2T''^3 && (T'' < 1) \\ &= 1 && (T'' > 1) \end{aligned} \tag{7}$$

where

$$T'' = \frac{w_*}{U}\left\{\frac{x}{h(x)} - \frac{x'}{h(x')}\right\}. \tag{8}$$

This factor was used to modify the base model (Equation (2)).

3. Data

Several Canadian governmental organizations in conjunction with the Ontario Hydroelectric Power Company conducted a comprehensive study of the Nanticoke Generating Station (NGS) plume during the summers of 1978 and 1979. The NGS is located on the north shore of Lake Erie, across from Erie, Pennsylvania. Emissions come from two 198 m stacks.

Boundary-layer measurements were taken using a combination of minisonde units, acoustic sounders, surface flux units and tethersonde units. The ground-based air quality measuring component consisted of eight systems including both mobile and fixed monitors. Details of the experimental set-up can be found in Portelli (1982).

For the purposes of this paper, we analyzed only the June 6, 1978 data. A high pressure system which was over the experimental area earlier in the week had by June 6th moved eastward, thus providing a general southwesterly gradient (onshore) flow.

TABLE I

Model input Parameters

June 6, 1978

Parameter	1200 EDT	1600 EDT
TIBL height (m)	$3.16x^{1/2}$	$5.6x^{1/2}$
Non-dimensional convective velocity w_*/U	0.18	0.25
Wind speed U (m s^{-1})	7.5	6.4
Plume buoyancy parameter F_0(m^4 s^{-1})	701	527
Emission rate Q (g s^{-1})	4181	6031
Brunt–Vaisala frequency N(s^{-1})	0.0181	0.0138
Effective stack height (m)	370	398

The model runs of 1200 and 1600 EDT were chosen for analysis. Input data for these runs appear in Table I.

Effective stack height was determined to be 370 m at a downwind distance of 14 km and 398 m at 4.6 km using lidar observations of the plume.

4. Discussion of Results

The base model for shoreline fumigation given in Section 3 was modified to account for slow entrainment of the plume into the TIBL using the downdraft concept (given by Equation (6)) and the empirical formulation obtained from physical modeling (given by Equation (7)). Three resulting models are referenced as below in the paper:

Model A – Base model for shoreline fumigation (assumes instantaneous mixing).
Model B – Base model modified using downdraft concept (assumes slow entrainment).
Model C – Base model modified using empirical results from physical modeling (assumes slow entrainment).

Figure 2 shows the ground-level concentrations predicted by the three models as a function of downwind distance for the 1200 EDT June 6, 1978 case. The origin is taken to be the coastline. Also shown in Figure 2 are observations made during the time period of the test selected. Comparing the results of the three models, Model B appears to predict larger downwind distance for maximum concentration, but the magnitudes of the maximum concentration remain approximately the same. Model C on the other hand predicts concentrations to be about 25% of those computed by Model A although the

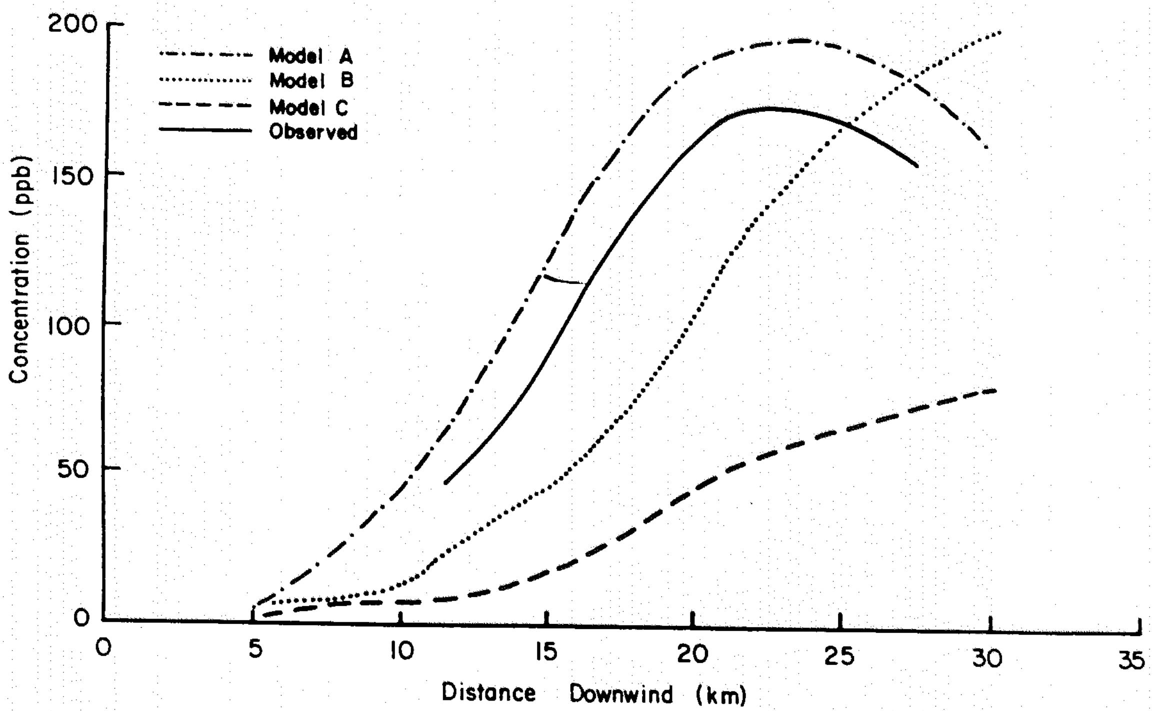

Fig. 2. Model concentration values for 1200 EDT, June 6, 1978. Also shown are the observed concentrations.

location of the maximum concentration is about the same as for Model B beyond 30 km. There is also an absence of a sharp peak in Model C. Observed values are closer to the results of Model A.

Results for another test case, 1600 EDT of June 6, 1978, are given in Figure 3. Location of maximum ground-level concentrations for Models B and C are farther downwind as shown in Table II. Magnitude of the maximum concentration predicted by Models B and C are about 50 and 20% of the value obtained by Model A which itself underpredicted the observed concentration by about 15%. Model A predicted the location of maximum concentration accurately.

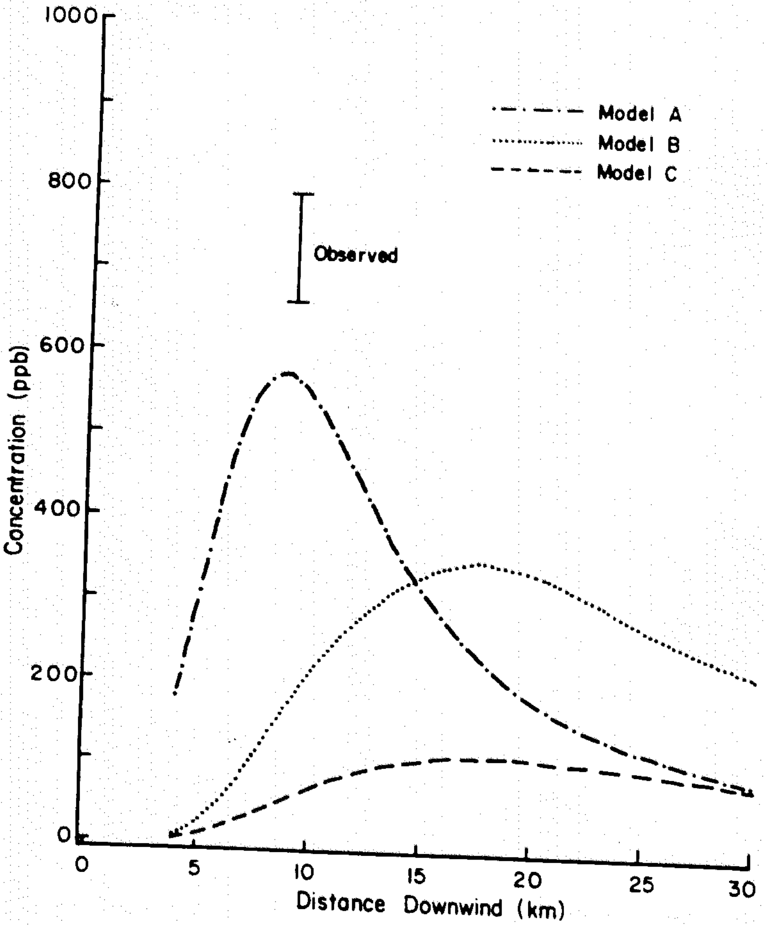

Fig. 3. Model concentration values for 1600 EDT, June 6, 1978. Also shown are the range of observations.

The results of this study indicate that the assumption of near-instantaneous mixing when the plume impacts the TIBL may not be a bad assumption at least for TIBLs that are highly convective as in this case (see Table I). Incorporation of the correction factors based on the downdraft concept or physical modeling formulation do not seem to improve the predictions. This indicates that the assumption of uniform mixing may be justified on the basis of the cumulative effects on the ground-level concentrations. This

TABLE II

Downwind distances (km) of maximum ground-level concentration for the three models

Data	Time (EDT)	Model A	Model B	Model C	Observation
June 6, 1978	1200	23	30	30	22
June 6, 1978	1600	9	18	15	9

makes the ground-level concentrations somewhat insensitive to the exact distribution in the vertical.

Finally it should be mentioned that non-uniform mixing could still be an important factor for fumigation cases involving slow-growing TIBLs and for stronger upwind stabilities than that encountered in the Nanticoke study.

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