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A STATISTICAL EVALUATION AND COMPARISON OF COASTAL POINT SOURCE DISPERSION MODELS

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Abstract—Fumigation caused by elevated sources in coastal areas has been simulated by two base models: the CRSTER Shoreline Fumigation Model (CSFM) and the Shoreline Dispersion Model (SLDM). This study consisted of evaluating the two base models along with variations of the SLDM model.

The statistical evaluation procedures involved the use of scatterplots, variances, total root mean square error and systematic root mean square error. In addition, an index of agreement value (d) was used in place of the standard statistical correlation coefficient (r) because of the restrictive nature of the correlation coefficient.

The 2-y comprehensive Nanticoke, Canada power plant study was used for evaluation purposes. The 13 test cases taken from the data base met the criteria of daytime onshore flow and sufficient land–water temperature difference.

The statistical evaluation indicated that the SLDM model performed better than the CSFM base model. This decision was based on (among other factors) the comparatively high index of agreement values (0.76 vs 0.46) for the SLDM model. Reasons for the comparatively poor performance of the CSFM model are given in terms of the Pasquill–Gifford curves vs the convective velocity scaling approach of the SLDM model and also the point source vs areal type dispersion approach. Two variations of the SLDM model were then evaluated. This evaluation indicated that the SLDM/downdraft model outperformed the SLDM/empirical model but was not better than the base SLDM model.

Key word index: Coastal Fumigation, Shoreline Dispersion, turbulence, sea breeze, Thermal Internal Boundary Layer, Internal Boundary Layer, diffusion.

1. INTRODUCTION

The growth of industrial and commercial operations near shorelines has created a need over the past several years for point source air pollution dispersion models that can handle the unique meteorological conditions present in the coastal environment. Typical applications of coastal dispersion models include regulation, stack design and defense concerns. Surface temperature gradients of 15° C within 20 km of the shoreline and vertical wind shears of 180° within 100 m of the surface (Lyons, 1975) make modeling of coastal point sources difficult.

Most coastal dispersion models need to include modules that determine the following:

(1) Thermal Internal Boundary Layer (TIBL) height,
(2) dispersion within the TIBL,
(3) dispersion in stable air upwind and
(4) effective plume height (penetration capability).

A reasonably thorough treatment of the unique atmospheric processes present in a coastal area can be included in a numerical model but such models are rarely used for operational or regulatory purposes because of their complexities. There are several statistical models (Lyons and Cole, 1973; Misra, 1980; Cole and Fowler, 1982) in use which compute ground-level concentrations based on the assumptions of Gaussian distribution or mixed layer hypothesis.

The purpose of this paper is to evaluate a set of coastal Gaussian dispersion models using data obtained from the Nanticoke shoreline fumigation project on the northern shore of Lake Erie. The models evaluated are CRSTER Shoreline Fumigation Model (CSFM) (Cole and Fowler, 1982), Shore Line Diffusion Model (SLDM) (Misra, 1980) and two variations of SLDM. The main objectives of this study are:

(1) Identification of accetable user-oriented coastal dispersion models and model components (e.g. Thermal Internal Boundary Layer formulation),
(2) identification of assumptions, uncertainties and applicability of a model and
(3) evaluation of existing coastal dispersion models using an air quality and meteorological data base.

2. THE THERMAL INTERNAL BOUNDARY LAYER (TIBL)

2.1. *The physics of the TIBL*

An important component of coastal dispersion models is the determination of the Thermal Internal Boundary Layer height (commonly called TIBL) that

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originates at the land–water interface and increases in height downwind. Interaction between the TIBL and a plume from an elevated coastal source influences the distribution of the ground-level concentration and the location of its maximum value. A convective internal boundary layer forms because of the differences between land and water temperatures. A stable (cool) marine airmass crossing a coastline must change its characteristics because of the temperature discontinuity at the shoreline. The change is accomplished by turbulence which acts as a transport mechanism for overland surface heat.

The TIBL interface generally increases parabolically inland from the shoreline until an equilibrium height is reached. A review of the literature by Stunder and SethuRaman (1985) indicates several approaches to determine the TIBL height. These include empirically derived equations to fit observational data (Prophet, 1961; Van der Hoven, 1967), techniques based on physical and dimensional considerations (Raynor *et al.*, 1975; Raynor *et al.*, 1979) and approximate analytical methods (Venkatram, 1977; Peters, 1975; Weisman, 1976).

Stunder and SethuRaman (1986) statistically evaluated the performance of these equations against observations from two independent TIBL field studies. They concluded that Weisman's (1976) equation performed the best in predicting TIBL height. The equation is:

$$h = \left(\frac{2H_0 X}{\rho c_p S U_{10}}\right)^{1/2} \tag{1}$$

where: H_0 = the overland heat flux ($\mathrm{wm^{-2}}$)
X = downwind distance from the shoreline (m)
ρ = density of air ($1.2 \times 10^3\ \mathrm{gm^{-3}}$)
c_p = specific heat at constant pressure ($0.24\ \mathrm{calg^{-1}\,k^{-1}}$)
S = overwater temperature gradient $\left(\frac{\partial\theta}{\partial Z}\right)$
U_{10} = wind speed at 10 m ($\mathrm{ms^{-1}}$) and
h = TIBL height.

It is important to note that some coastal dispersion modelers (Van Dop *et al.*, 1979; Misra, 1980) prefer to simplify the TIBL equations such that:

$$h = A\,X^{1/2} \tag{2}$$

where:

A = a factor containing different physical parameters necessary for TIBL determination.

In the case of Equation (2) for example, $A = 2H_0/\rho c_p SU$. Values of A can be determined directly with a knowledge of h at a known downwind distance.

2.2. *Effect of TIBL variation on dispersion*

Two important physical processes concerning dispersion in coastal regions are fumigation and trapping. Plumes emitted into the stable marine air at the shoreline ($X = 0$) normally move inland with onshore flow and at some point intersect the deepening TIBL (see Fig. 1). Intense downward mixing at the point of TIBL impaction can cause high ground-level concentration. Plumes have been observed to travel 20–30 km downwind before fumigating (Portelli, 1982).

Trapping conditions occur when stacks are located within the TIBL at some inland distance such that plumes are emitted into the convectively mixed TIBL and are effectively capped by the TIBL interface. If a plume is buoyant enough and a stack is located close to the TIBL interface the plume may actually penetrate into the stable marine air and then fumigate back into the TIBL further downwind. Even small differences between predicted TIBL height values could cause serious errors in predicting the location of the ground-level fumigation and hence the location of maximum

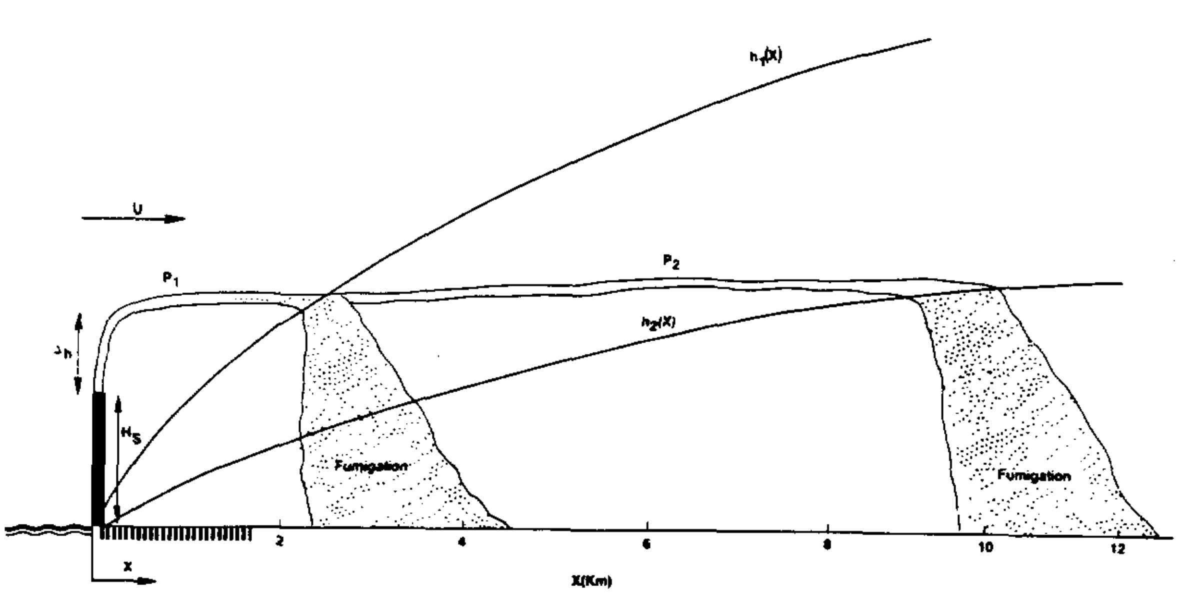

Fig. 1. Typical dispersion pattern in coastal areas.

ground-level concentration for plumes originating in the stable marine air (Stunder and SethuRaman, 1986).

3. THE COASTAL DISPERSION MODELS

Fumigation is a transitional process which involves a plume in a stable layer impinging upon an unstable turbulent layer. The impingement may be because of vertical, temporal or spatial turbulent layer growth. Bierly and Hewson (1962) were the first to define three different types of fumigation. They are:

Type I: Nocturnal inversion breakup

Type II: Flow of air over an artifical heat source (i.e. urban areas)

Type III: Continuous, occurring over natural heat sources such as shorelines.

We are concerned with Type III fumigation which occurs during onshore flow and generally during daylight hours. Plumes emitted into the stable marine air eventually impinge upon the growing TIBL and fumigate downward as outlined in the previous section.

3.1. *The Lyons and Cole* (1973) *Model/CRSTER Shoreline Fumigation Model* (*CSFM*)

Lyons and Cole (1973), in a study of a large fossil fuel plant on the western shore of Lake Michigan, presented a modification of Turner's fumigation scheme (Turner, 1970) for shoreline applications.

The Lyons and Cole (1973) model divides the downwind dispersion area into three zones:

Zone I: Undisturbed dispersion zone (X_1)

Zone II: Plume fumigation zone (X_2)

Zone III: Plume trapping zone (X_3).

A diagram depicting the vertical and horizontal plume geometry appears in Fig. 2.

The assumptions of the model are:

(1) 'Steady-state' concentration—each concentration represents 10 minutes of sampling time

(2) Flat terrain

(3) No initial plume dilution and

(4) For a given plume, wind direction and speed are constant in space.

Therefore the effect of shear is neglected.

In zone I, where X_1 is a function of $(X, Z:H_e)$ and H_e is the effective stack height, the elevated plume is emitted into a homogeneous stable layer and therefore remains unmodified in shape. Plume dispersion in the stable layer although small is based on the Pasquill–Gifford criteria and is represented by $\sigma_{y,z}(X, s)$ and $\sigma_z(X, s)$.

Zone II $(X_2, Z:H_e)$ applies to the region where the plume impacts and is being entrained into the TIBL. Figure 2 depicts this zone as falling between points X_B (beginning of fumigation) and X_E (end of fumigation).

The beginning of fumigation at X_B occurs at the point on the TIBL interface, $h = H_e - 2.15\sigma_z(X, s)$, which is similar to the approach by Turner (1970). This is the position where turbulence begins to affect the lower portion of the plume. Consequently, the point at which the majority of the plume has been mixed into the TIBL (X_E) is determined by $h = H_e + 2.15\sigma_z(X, s)$.

An important feature to note about zone II is that the profile of concentrations below the TIBL is considered nearly uniform in the vertical. Horizontally, the plume is treated as Gaussian. Concentrations in zone II can be found by using the equation.

$$C(X) = \frac{Q}{\sqrt{2\pi}\,\sigma_{yf}(X,s)\,Uh}\left[\int_{-\infty}^{P}(2\pi)^{-1/2}\times\exp\left(\frac{-P^2}{2}\right)\mathrm{d}P\right]\exp\left[\frac{-1}{2}\left(\frac{Y}{\sigma_{yf}(X,s)}\right)^2\right] \quad (3)$$

where σ_{yf} is the horizontal spread of the plume in the fumigation zone represented by:

$$\sigma_{yf}(X, s) = \sigma_y(X, s) + \frac{H_e}{8}. \quad (4)$$

A correction factor of $H_e/8$ (based on Turner, 1970) is

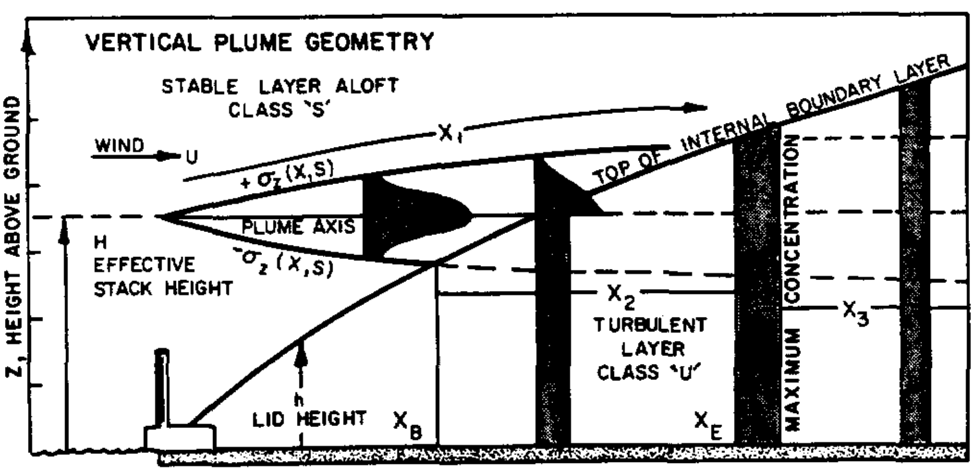

Fig. 2. Plume geometry of Lyons and Cole (1973) model. $\sigma_z(x, s)$ represent vertical dispersion coefficients. X_B, X_E represent the beginning and end points of fumigation.

thus added to $\sigma_{y,s}(X, S)$ to account for increased dispersion in the TIBL.

The integral in Equation (3) is the area under the standard normal distribution where P is the value of a variable having the standard normal distribution. This gives the proportion of the normally distributed plume that has entered the TIBL at some distance X. The quantity ranges from 0 to 1. In this case, P is defined to be:

$$P = \frac{h - H_e}{\sigma_z(X, s)}. \quad (5)$$

The factor P accounts for the portion of the plume that is mixing downward after TIBL impaction. The concentration is determined at the point X_E downwind, where it is assumed that the entire plume has been mixed downward.

In zone III the plume is assumed to be trapped with a variable TIBL lid height as an upward boundary. Concentrations once again are assumed to be uniform in the vertical below the TIBL. The plume trapping formula of Turner (1970) along with a virtual point source method to determine the new dispersion coefficient $\sigma_y(X', U)$ is used in this zone.

Lyons (1975) indicates that the three zone approach of the model allows flexibility in terms of handling different shoreline dispersion situations. A plume emitted from a tall stack may remain in zone I for a long period of time and can be modeled using the elevated plume approach of Turner (1970). A plume impacting the TIBL and then fumigating (zone II) can be simulated using the approach of Equation (3), while a plume emitted from a stack located in the TIBL can be modeled using the plume trapping approach.

The CRSTER Shoreline Fumigation Model (CSFM) developed by Cole and Fowler (1982) is an interactive version of EPA's Single-Source CRSTER model which has been modified to handle shoreline dispersion conditions. The model consists of four main modules: two plume rise modules, a diffusion module and a fumigation module. Concentration calculations (at one time) can be made at 180 receptors arranged in five rings with 36 receptors in each ring. The CSFM model has not been tested on field data prior to this study.

The fumigation module incorporates the Lyons and Cole (1973) scheme described above with some modifications. The model assumes (as does the Lyons and Cole, 1973 model) that a pollutant parcel entering the TIBL from the stable layer is instantaneously uniformly vertically mixed. However, unlike the Lyons and Cole (1973) model, which treats dispersion in the fumigation zone as $\sigma_{yf} = \sigma_y + H_e/8$, CSFM assumes that the plume is gradually eroded by the TIBL such that different segments of the entrained plume disperse differently. The concentration at a particular receptor X_j is therefore affected by all of the plume segments which have been entrained into the TIBL upwind such that:

$$C_j = \sum_{i=1}^{n} C_{ji} \quad (6)$$

and

$$C_{ji} = \frac{Q_i}{\sqrt{2\pi}\,\sigma_{yf_{ij}} U h(x)} \quad (7)$$

where $\sigma_{yf_{ij}}$ is the dispersion coefficient for plume segment i at receptor location j. The quantity Q_i is the mass per second contained in plume segment i and is computed for every 0.2-km interval. Q_i is determined by:

$$Q_i = Q\left[\int_{-\infty}^{P} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-P}{2}\right)^2 \mathrm{d}P\right]_{\text{at } x_i} - \left[-\int_{-\infty}^{P} \frac{1}{\sqrt{2\pi}} \exp -\left(\frac{P}{2}\right)^2 \mathrm{d}p\right]_{\text{at } x_i - 1} \quad (8)$$

where x_i represents the downwind distance at plume segment i.

Plume rise is determined using appropriate methods based on the stack location. If the plume is emitted into the stable air, a plume rise formula with lake stability is used (Briggs, 1975). When the stack is located below the TIBL (i.e. inland stack or TIBL formation over water) the potential exists for either trapping or penetration. In this case, the final plume rise is first determined using Briggs (1975) formulations for unstable air. If the resulting rise leaves the plume below the TIBL, trapping occurs since the plume is not buoyant enough to penetrate the TIBL interface. Penetration occurs if the resulting rise is greater than TIBL height (i.e. the plume punctures through the TIBL). The height of penetration is then determined and a two staged plume rise model suggested by Holtzworth (1978) is utilized.

3.2. *The Misra* (1980) *Shoreline Dispersion Model (SLDM)*

Assumption of uniform mixing in the vertical inside the TIBL is also used in the Shoreline Dispersion Model (SLDM) by Misra (1980). The SLDM model assumes that movement of pollutants into the TIBL is caused by two mechanisms:

(1) entrainment of the plume downwind by the growing TIBL and
(2) plume dispersion in stable air.

It is also assumed that the dispersion of pollutants in the stable layer aloft and within the TIBL proceed independently.

Defining (x', y') as being points located on the TIBL interface h at some downwind distance x, Misra (1980) assumes an areal source to exist at each of these points such that $F(x', y')\mathrm{d}x'$ represents the net flux of pollutants through that area source. The source strength is provided by the concentration field within the stable layer (C_s) and also by the variation of the TIBL.

A distribution function $P(x, y, z, x', y')$ is used to determine the concentration flux of pollutants through the TIBL interface such that:

$$C(x', y', z') = \int_{y'=-\infty}^{\infty} \int_{x'=0}^{x} F(x', y) \times P(x, y, z, x', y')\mathrm{d}x'\mathrm{d}y'. \quad (9)$$

Assuming that we are interested in centerline concentrations, the ground-level concentration along the centerline of the plume is given by:

$$C(x, y) = \frac{Q}{2\pi h(x)} \int_0^x \frac{\sigma'^{-1}}{U_m} \exp\left\{\left(\frac{h(x') - H_e(x')}{\sqrt{2}\sigma_{z,s}(x')}\right)^2 - \frac{y^2}{2\sigma'^2}\right\} \frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{h(x') - H_e(x')}{\sigma_{z,s}(x')}\right)\mathrm{d}x' \quad (10)$$

where

x' = point downwind at which plume begins to intersect TIBL (m),

$\sigma_{z,s}$ = stable air dispersion coefficient (m),

$\sigma'^2 = \sigma_{y,s}^2(x') + \sigma_{y,h}^2(x, x')$,

$\sigma_{y,h}$ = TIBL dispersion coefficient,

U_m = mixed layer mean wind speed ($\mathrm{m\,s^{-1}}$).

Misra (1980) adopted the stable layer dispersion parameters to be based on the assumption that diffusion in the stable layer is due to plume-induced turbulence:

$$\sigma_{z,s} = a_1\left(\frac{F_0}{U_s}\right)^{1/3} t^{2/3}, \quad t < \frac{4.5}{N} \quad (11)$$

and

$$\sigma_{y,s} = a_2\left(\frac{F_0}{U_s}\right)^{1/3} t^{2/3}, \quad t \geqslant \frac{4.5}{N} \quad (12)$$

where N = Brunt-Vaisalla frequency ($\mathrm{s^{-1}}$),

F_0 = buoyancy flux ($\mathrm{m^4\,s^{-1}}$),

U_s = stable layer wind speed.

Characterization of σ_y in the TIBL is taken to be a function of the convective velocity w_* where:

$$w_* = \left(\frac{gH_0h}{\rho c_p T}\right)^{1/2}. \quad (13)$$

Convective velocity w_* was assumed to be constant in the TIBL. Following Lamb (1978), $\sigma_{y,h}$ was taken to be:

$$\sigma_{y,h}(x) = \frac{1}{3}\left(\frac{w_*}{U_m}\right)(x - x'), \quad x' < x \leqslant \frac{hU_m}{w_*} \quad (14)$$

$$\sigma_{y,h}(x) = \frac{1}{3}\left(\frac{w_*}{U_m}\right)h^{1/3}(x - x')^{2/3}, \quad x' < x > \frac{hU_m}{w_*}. \quad (15)$$

This type of dispersion coefficient parameterization has also been recently used in the Maryland Power Plant Siting Program (PPSP) model by Weil and Brower (1984) with good success.

3.3. *The Deardorff and Willis* (1982) *empirical modification to SLDM*

The approaches of Lyons and Cole (1973) and Misra (1980) assume that the plume is instantaneously mixed downwind after impacting the TIBL. However, variability in TIBL height and the process of air mass modification may require a longer time for total plume fumigation.

Water tank laboratory experiments involving entrainment of a tracer into a convectively mixed boundary layer were recently performed by Deardorff and Willis (1982) with the goal of simulating realistic convective dispersion. The TIBL was assumed to undulate between heights h_1 and h_2 because of the presence of convective eddies. The change in TIBL height ($h_2 - h_1$) was observed to be 30%. For modeling purposes, the TIBL was assumed to be represented by a mean value.

The model assumes that the plume has little vertical dispersion (small $\sigma_{z,s}$) before intersecting the TIBL interface. A fraction of the potential fumigant $[A(t)]$ is entrained over a time t with $0 \leqslant A \leqslant 1$. This adjustment factor, A, is given in terms of dimensionless quantities as:

$$A = 3T''^2 - 2T''^3 \quad (T'' < 1)$$
$$= 1 \quad (T'' > 1) \quad (16)$$

where:

$$T'' = \frac{w_*}{U}\left\{\frac{x}{h(x)} - \frac{x'}{h(x')}\right\}. \quad (17)$$

This factor was used to modify the base model discussed in a previous section [Equation (10)].

According to the experiments by Deardorff and Willis (1982), only 16% of the well-mixed fumigant from any particular entrained parcel will appear at ground-level one time constant later, while 84% is brought down three time units after the entrainment and 100% after four time units. Thus the location of maximum downwind ground-level concentration is related by empirical data to the vertical plume TIBL distribution.

3.4. *The downdraft modification to SLDM*

The convective nature of the boundary layer which occurs under the TIBL interface contains both updrafts (thermals) and downdrafts. Probability density analysis of vertical velocities in a convective boundary layer (Lamb, 1982) indicated that downdrafts occupy more than half the horizontal reference plane through the convective boundary layer.

Misra (1981) proposed a revision to the typical Gaussian type modeling approach based on the prevalence of the downdrafts in the convective boundary layer. The Misra (1981) downdraft model assumes that the pollutant particles are non-buoyant and that diffusion in a convective boundary layer is affected by downdrafts and updrafts. Complete details of the original model are found in Misra (1981). To apply this approach to the SLDM model, we assumed that the processes related to downdrafts are responsible for vertical dispersion within the TIBL from an areal source at the plane of intersection between the plume and the TIBL. The equation which represents the ground-level concentrations affected by TIBL downdrafts is then given by Stunder *et al.* (1985) as:

$$C = \frac{\sqrt{2\pi}\, f_1(Z_s)}{\pi f_1(Z_s)\sigma_w(Z_s)} \int_0^x \frac{\sigma^{-1}}{2\pi(x-x')} \exp\left[\frac{1}{2\sigma_{wd}^2(Z_s)}\right.$$
$$\frac{g(z) f_1(Z_s) U_{10}}{x-x'} - \overline{w_d}(Z_s) - \left(\frac{h-H_e}{\sqrt{2\pi}\,\sigma_{z,s}}\right)^2$$
$$\left. - \frac{y^2}{2\sigma'^2}\right] \frac{d}{dx'}\left[\frac{h-H_e}{\sigma_{z,s}(x')} dx'\right] \qquad (18)$$

where $f_1(Z_s)$ = a turbulence parameter given by Lenschow and Stephens (1980)

$g(Z)$ = an integral form (Misra, 1981) that defines the downdraft velocity at plume intersection

σ_w = standard deviation of the vertical velocity determined from relations given by Lenschow and Stephens (1980).

Appropriate values (based on the Nanticoke study, Portelli, 1982) that determine $f_1(Z_s)$, $g(z)$ and σ_w were substituted in Equation (18).

The statistical model for the convective boundary layer has been evaluated by Misra (1981) using Lamb's (1979) numerical model results. The downdraft modification to SLDM has not been previously evaluated.

4. THE NANTICOKE STUDY

The characterization of dispersion in coastal areas has been investigated during several field experiments. Early coastal experiments have been reported by Prophet (1961) and Munn and Richards (1967). Later experiments include work in the Great Lakes area (Lyons, 1977) and on the Atlantic Coastline (Raynor *et al.*, 1983).

One of the most comprehensive coastal dispersion experiments, the Nanticoke Environmental Modeling Program (NEMP), was conducted at the Nanticoke Generating Station (NGS) during the summers of 1978 and 1979. The NGS operated by the Ontario Hydro Company is located on the north shore of Lake Erie across from Erie, PA, and consists of two stacks, each of which is 198 m high. Each stack had four flues with a load capacity of 500 MW each and a flue diameter of 5.49 m. Total plant load capacity was 4000 MW with approximate emission of 156,000 tons of SO_2 per year. Plume rise was observed to average around 400 m from stack base (Ontario Ministry of Environment, 1979).

Boundary layer measurements during the study period were taken using a combination of minisonde units, acoustic sounders, surface flux units and tethersonde units. The minisonde systems were mobile, therefore allowing flexibility in terms of deployment. The system consisted of an instrument package containing a temperature sensor and a transmitter attached to a free floating balloon. Wind speed and direction were obtained by a double theodolite tracking system. Acoustic sounder units were positioned at various distances inland and were able to complement the minisonde systems in determining TIBL structure. A micro-meteorological tower was located inland to determine the fluxes of momentum, sensible and latent heat and correlate these fluxes to TIBL evolution. The tethersonde units provided wind, humidity and temperature information up to 600 m and were particularly useful in the first several kilometers inland from the coast.

Wind measurements were taken at an 85 m tower located 10 m inland and also at the stack height. The ground based air quality measuring component consisted of eight measuring systems including both mobile, *in-situ* and fixed monitors. A mobile lidar unit was used to obtain plume height, its bearing and dispersion characteristics (σ_y, σ_z). Three mobile correlation-spectrometer (COSPEC) units were used to obtain vertically integrated SO_2 concentrations.

Two of the roving COSPEC units also had SIGN-X SO_2 monitors which obtained ground-level concentrations. A helicopter with a SIGN-X instrument was used to obtain vertical profiles of pollutant concentrations. Sixteen Ontario Hydro Power Company Phillips SO_2 type monitors reported 1-h averaged concentrations. In addition, mobile chemistry units which contained gas analysis systems were deployed for plume chemistry measurements. Portelli (1982) describes in detail the Nanticoke experimental design.

5. MODEL EVALUATION

In this section we present the statistical evaluation protocol, data base criteria and discussion of results.

5.1. *Statistical protocol and data base criteria*

The increase in air pollution regulations during the past decade has stimulated regulatory agencies and industry to develop statistical methods for model evaluation. Model performance techniques outlined by Fox (1981) included both residual (difference) analysis which allows a quantitative estimate of ($\overline{O} - \overline{P}$) and correlation which allows a measure of agreement between O and P. The residual analysis methods by Fox (1981) include:

(1) Mean Bias Error (MBE)

$$N^{-1} \sum_{i=1}^{n} (P_i - O_i) \qquad (19)$$

(2) Variance of the difference

$$S_d^2 = (N-1)^{-1} \sum_{i=1}^{n} (P_i - O_i - MBE)^2 \qquad (20)$$

(3) Gross error of the difference, Mean Square Error (MSE)

$$MSE = N^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \qquad (21)$$

or Root Mean Square Error ($RMSE$)

$$RMSE=\left[N^{-1}\sum_{i=1}^{n}(P_i-O_i)^2\right]^{1/2}. \qquad (22)$$

The correlation analysis methods of Fox (1981) consisted of:

(1) time correlation ($r\Delta t$) where r is the correlation coefficient;

(2) space correlation $r_s \pm f[C_0(x,t); C_p(x,t)]$ where C_o, C_p are the observed and predicted concentration values and

(3) combination of time and space.

Willmott (1982a) proposed several modifications to the Fox (1981) recommendation which are given below.

Willmott and Wicks (1980) presented rainfall data that showed statistically significant r and r^2 values to be unrelated to the $\bar{O}-\bar{P}$ differences. They have shown that small differences between O and P could occur with low or negative values of r. The statistics r and r^2 do describe proportional changes (either increasing or decreasing) with regard to the means of the two quantities in question. However, distinctions between the type or magnitudes of variables are not indicated by the value of r. Other studies (Willmott, 1982b) have also shown how the use of r and r^2 can be misleading in interpreting model accuracy. Venkatram and Vet (1981) have also indicated that the correlation analysis is of little value if the observed variance is close to the expected variance between model predictions and measurements.

Willmott (1981, 1982a, 1984) suggested using an index of agreement (d) and the Root Mean Square Error ($RMSE$) to circumvent the problems associated with correlation coefficients, MBE and S_d^2 type parameters. The index of agreement can be interpreted as a measure of how error-free a model predicts a variable. Thus, the index d determines the extent to which magnitudes and signs of the observed values about $\bar{O}$ are related to the predicted deviations about $\bar{O}$. It is assumed that O and $\bar{O}$ are error free. The maximum possible distance that two observations can be apart may be described by:

$$|P_i-\bar{O}|+|O_i-\bar{O}|. \qquad (23)$$

Squaring Equation (23) and summing over all observations leads to a potential error (PE) variance (Willmott, 1981) and therefore the condition $0 \leqslant (RMSE)^2 \leqslant N^{-1}PE$ is satisfied. The statistical descriptive relative error measure which indicates the degree to which P approaches O can then be written as:

$$d=\frac{1-\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(|P_i'|+|O_i'|)^2} \qquad 0\leqslant d\leqslant 1 \qquad (24)$$

where $P_i'=P_i-\bar{O}$ and $O_i'=O_i-\bar{O}$. The unexplained error that is left over is contained in the numerator of Equation (24). The index d therefore allows for sensitivity toward differences in O and P as well as proportionality changes. The index d is standardized such that cross comparisons of magnitudes can easily be made between models. A value of 1.0 indicates perfect agreement between O and P values.

The index d should not be interpreted exclusively since d becomes unstable when the denominator is small. It will therefore be better to use index d in conjunction with the difference measures such as the mean square error and its components, the systematic MSE (MSE_S) and the unsystematic mean square error (MSE_u). Difference measures provide the most rigorous and useful information regarding overall model performance. However, models contain both systematic and unsystematic errors. Systematic errors result from causes which occur consistently. Unsystematic errors consist of a number of small effects such as the imprecision of a constant. Some of these effects are positive and some are negative in terms of affecting the final output value.

The best model therefore has a systematic difference of zero since it should explain most of the systematic variation in observed values O, while the unsystematic difference should approach the MSE. The value of MSE should be minimized so that the model is predicting at peak accuracy. A large value of MSE_u may indicate that the model is as good as possible under the present conditions.

In terms of mathematical notation, the systematic mean square error is the error caused by model additive or proportional problems and can be expressed as:

$$MSE_S=N^{-1}\sum_{i=1}^{n}(\hat{P}_i-O_i)^2 \qquad (25)$$

where $\hat{P}=a+bO_i$ and a and b are regression coefficients.

The unsystematic mean square error is:

$$MSE_u=N^{-1}\sum_{i=1}^{n}(P_i-\hat{P}_i)^2. \qquad (26)$$

The total MSE can therefore be written as:

$$MSE=MSE_S+MSE_u. \qquad (27)$$

The values of $RMSE$s (square roots of the MSEs) are generally computed to make the numbers easier to use for qualitative or quantitative comparisons. The total $RMSE$ may be written as:

$$RMSE=\sqrt{RMSE_S^2+RMSE_u^2}. \qquad (28)$$

Finally, in addition to $RMSE_S$, $RMSE_u$ and d, computation of summary measures such as $\bar{O}$, $\bar{P}$, S_o^2, and S_p^2 along with simple linear regression will be of use. In this study, while we follow the summary measures and linear regression approach recommended by Fox (1981), we have included the difference measures and the index of agreement (d) suggested by Willmott (1982a) for model evaluation. We have chosen not to use statistics based on traditional highest and second highest concentration values and frequency distribution since the data represents more of a case description of coastal fumigation as opposed to the more typical monthly or annual climatological receptor analysis.

5.2. *Statistical analysis*

The 13 test periods (listed in Table 1) were selected because they have met the established criteria (Cole and Lyons, 1972; Lyons, 1975) for onshore coastal fumigation occurrences. The criteria are:

(1) Onshore flow within $\pm 10°$ relative to the angle of the shoreline (i.e. the angle of the shoreline with respect to N at NGS is 80°; therefore, the allowable windflow angles for fumigation to occur are 90–250°).
(2) Hours of occurrence from 7 a.m. to 7 p.m. (daytime).
(3) Hourly wind speed greater than $2 \mathrm{m\,s^{-1}}$.
(4) Land–water temperature difference greater than 0.5° C.

It is also important to note that the tests only occurred under stable marine air conditions. No cases were observed with neutral or unstable marine air characteristics. Concentration values were computed up to 30 km downwind at 1-km intervals.

Scatterplots of the predicted vs observed values for each model (Figs 3–6) were created since they represent an initial means of readily displaying the various relationships between O and P values. The various general error patterns of the models were apparent with respect to the $a = 0$, $b = 1$ prediction line. The SLDM model appeared to have the least scatter, although the models on the whole exhibit considerable scatter especially for large concentration values. Three of the models tend to show an underprediction of concentration values, while the SLDM model tends toward overprediction of concentration values. The scatterplots provided a crude initial means of determining under and overprediction, however, they indicate nothing about the quantitative magnitude of error or the accuracy.

Table 1. List of tests used for model comparison

Test	Date	Time (EDT)
1	1 June 1978	1100
2	1 June 1978	1200
3	1 June 1978	1300
4	1 June 1978	1400
5	1 June 1978	1500
6	6 June 1978	1200
7	6 June 1978	1400
8	6 June 1978	1500
9	6 June 1978	1600
10	6 June 1978	1700
11	13 June 1979	1700
12	14 June 1979	1400
13	14 June 1979	1600

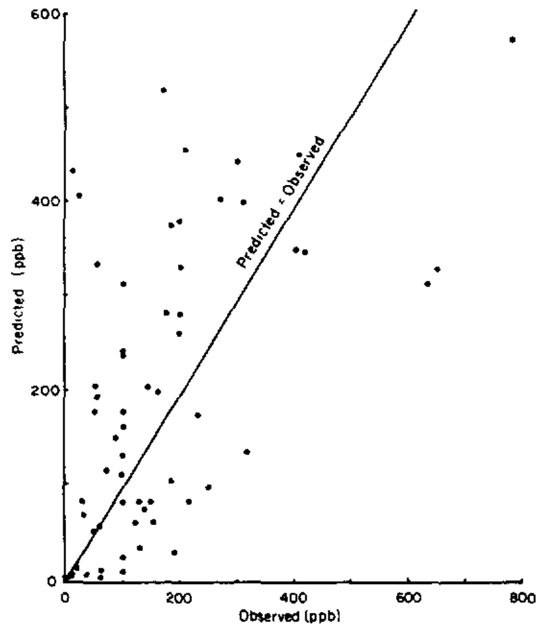

Fig. 3. Observed vs predicted concentration values for the SLDM model.

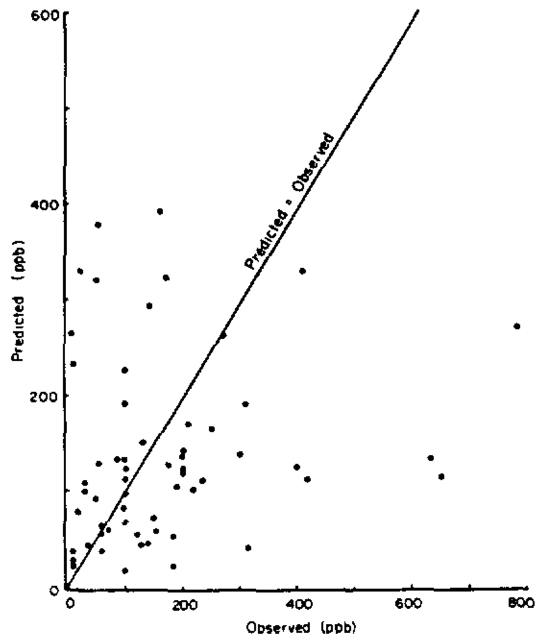

Fig. 4. Observed vs predicted concentration values for the CSFM model.

A listing of the various summary measures, regression coefficients and difference measures that give a better understanding about the degree of error appear in Table 2. The $\bar{O}$ vs $\bar{P}$ summary measures indicate that on the average, the CSFM, SLDM/empirical modification and SLDM/downdraft modification underpredict concentration values while SLDM overpredicts. The SLDM model exhibited the smallest average error of 26 while the empirical

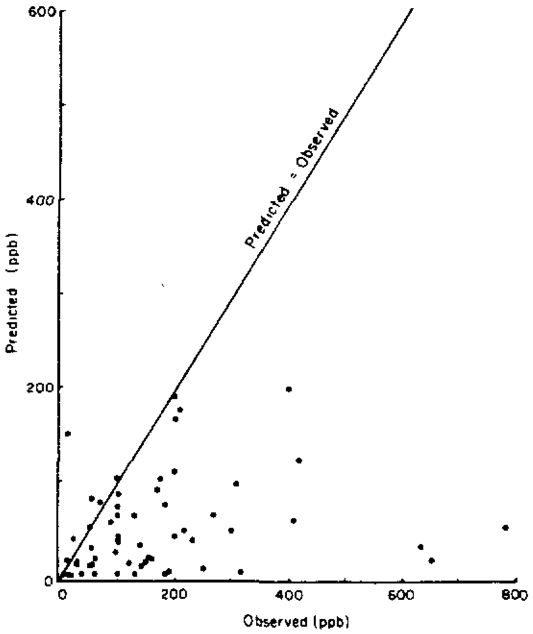

Fig. 5. Observed vs predicted concentration values for the SLDM/empirical modification model.

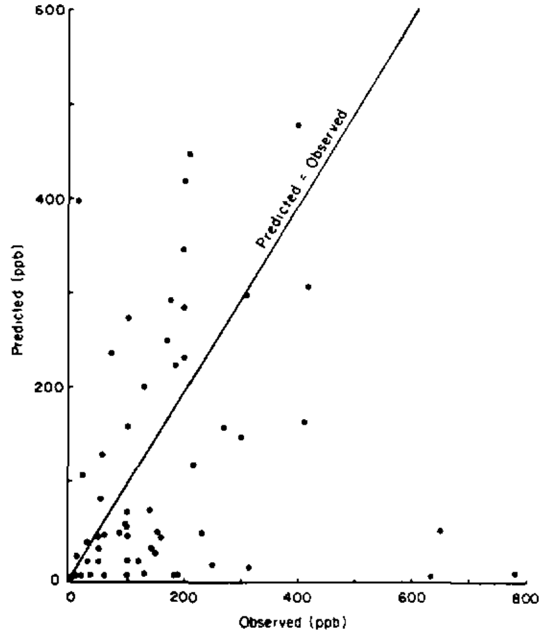

Fig. 6. Observed vs predicted concentration values for the SLDM/downdraft modification model.

modification had the largest average error of −117. A comparison of S_o and S_p with regard to how close the two deviation quantities approach each other gives a relative indication of how well a model is reproducing the observed variance. Thus, from Table 2 it appears that the SLDM model is best able to describe the observed variability.

The two measures which are not univariate summary statistics or difference statistics are the regression coefficients. They have been included here for completeness since they are used to compute the more representative measures such as *RMSE*s. There are two problems in the interpretation of a and b. The first problem is that the two coefficients are not independent of one another and the second related problem involves correlation analysis between the coefficients and other summary variables. Ideally, however, we would like to see intercept $a = 0.0$ and slope $b = 1.0$. This condition is better met by the SLDM model. It is difficult to interpret the other model coefficient values for other models since some of the 'a' values are rather large, yet the 'b' values are small (see for example the SLDM model with the empirical modification, Table 2).

The difference measures such as *RMSE* generally agree with the univariate summary measurements with regard to the capabilities of the various models to predict concentration values. The analysis of *RMSE* from Table 2 indicates that the SLDM has the least overall *RMSE*. The SLDM model also fits the criteria of the systematic error, being comparatively small (although not 'close' to zero) and the unsystematic error approaching the overall *RMSE*.

The difference measures for the CSFM model show the $RMSE_s$ to be similar to the downdraft model, but still relatively higher than the SLDM model. The SLDM/empirical modification has a small difference of six between overall *RMSE* and $RMSE_s$, which implies that this modification might contain numerous systematic errors. Table 2 also indicates that the SLDM/downdraft modification performs better in terms of both overall *RMSE* and $RMSE_s$ values than the SLDM/empirical modification.

The relatively comprehensive difference measure of

Table 2. Quantitative measures of coastal dispersion model performance, overall model performance

Equations	Summary measures				Linear regression		Difference measures			
	$\bar{O}$	$\bar{P}$	S_o	S_p	a	b	*RMSE*	$RMSE_u$	$RMSE_s$	d
CSFM	164	134	158	95	118	0.10	193	128	145	0.46
SLDM	164	190	158	156	99	0.56	148	128	74	0.76
SLDM/empirical modif.	164	47	158	50	36	0.10	193	48	187	0.45
SLDM/downdraft modif.	164	108	158	131	84	0.15	172	93	144	0.50

Note. The units of concentration values are in ppb.

the ability of a coastal dispersion model to predict the downwind concentration, the index of agreement (d) suggests (following Willmott, 1982a) that the percentage of the potential for error in predicting concentrations has been explained by the model. Thus for the SLDM model, 67% of the potential for error has been explained by the model. The d values for the other models are in the middle to upper 40th percentile range which is considerably less than the SLDM model.

5.3. *Discussion of results*

The preceding results suggest that the appropriate rankings of the models in terms of their performance should be:

(1) SLDM
(2) SLDM/downdraft modification
(3) CSFM
(4) SLDM/empirical modification.

The high d value implies that there is lower error in the SLDM model results when compared to the other models. The two variations of the SLDM (empirical modification and downdraft modification) show higher degrees of systematic error which would suggest that these variations do little to enhance the concentration predictability of SLDM.

We believe that the SLDM/downdraft model ranks second in terms of potential accuracy for several reasons. The d value of the SLDM/downdraft model when compared to the two remaining models (SLDM/empirical modification and CSFM) is higher. Secondly, even though the systematic errors of both the SLDM downdraft model and the CSFM model are about equal, the contribution due to unsystematic errors do indicate a big discrepancy, with the SLDM downdraft model having the better *RMSE* value. Thirdly, values of the regression slope suggests that the SLDM downdraft model outperforms the remaining two models. Lastly, the summary univariate statistics, although not indicating a closeness in the average sense of $\bar{O}$ and $\bar{P}$ for the downdraft model compared to the CSFM model, certainly show the better ability of the downdraft model to reproduce the scatter as evidenced by the S_o and S_p differences.

The CSFM model, while ranking a close third behind the SLDM downdraft model, outperforms the SLDM/empirical modification particularly in the areas of univariate summary measures and RMSEs. In terms of univariate summary measures, the CSFM model clearly shows a closer agreement when comparing $\bar{O}$ and $\bar{P}$ than the SLDM/empirical modification. The CSFM also shows a somewhat closer agreement between S_o and S_p values than the SLDM/empirical modification. A *RMSE* analysis between the two models illustrates the quantitative problems associated with the empirical modification. The $RMSE_s$ nearly approaches the overall *RMSE*, indicating systematic errors in the SLDM/empirical modification particularly given the wide difference in the univariate summary measures of $\bar{O}$ and $\bar{P}$ and also S_o and S_p. For these reasons, the SLDM/empirical modification is ranked fourth.

It is important not to base the argument for the best performing model just on the quantitative statistical values of the model results. Significant physical differences exist between the two base models (i.e. CSFM and SLDM) and between SLDM and its variations (empirical and downdraft modifications). These physical differences can only be adequately presented in the qualitative descriptive sense by looking at the physical methods (such as treatment of dispersion coefficients) that are used by these models.

Physical differences between the base models of CSFM and SLDM (along with its variations) are found in two key areas:

(1) treatment of the dispersion coefficients (σ_y and σ_z) in both the stable marine air and the convective TIBL and
(2) uniform vs non-uniform mixing approaches.

The problem of the change in dispersion coefficients across the TIBL interface was addressed as early as the original Lyons and Cole (1973) model. The split sigma concept used in CSFM relies on the basic premise that the horizontal dispersion in the stable zone can be characterized by a dispersion coefficient $\sigma_{y,s}$ which is determined by the standard Pasquill–Gifford (PG) curves. It is well known that the PG coefficients were constructed from data taken over flat homogeneous terrain and refer to ground-level neutrally buoyant tracer sources and not elevated sources. The averaging time to determine the coefficients was 3 min and the concentration measurements were made out to only about 800 m from the ground-level release.

Pasquill and Smith (1983) caution against the application of the PG coefficients without regard to terrain or circumstances. Use of the PG-type coefficients has been shown in summary form to be unrepresentative of diffusion in coastal areas (see for example MacRae *et al.*, 1983). In addition, an application of the EPA RAM Air Quality Model modified by using the Lyons and Cole (1973) approach for a power plant in Wisconsin (Ellis *et al.*, 1979) indicated that the PG coefficients were not helpful in predicting ground-level concentrations under fumigation conditions. The use of Turner's stability criteria by CRSTER has also been shown to be biased toward neutral stability by Weil and Jepson (1977) and Weil (1979).

The SLDM approach on the other hand allows for direct calculation of $\sigma_{y,s}$ based on the influence of self-induced plume turbulence created by plume momentum and buoyancy. This means that following Briggs (1975), $\sigma_{y,s}$ is proportional to plume rise only, since ambient turbulence in the stable air is negligible. This is physically more realistic than the method for determining $\sigma_{y,s}$ adopted by CSFM which relies on the empirical and limited PG curves in the stable air and the $H_e/8$ correction applied to $\sigma_{y,s}$ to determine σ_{yf} (lateral plume dispersion within the TIBL). The more realistic and useful 'state of the art' method of determining horizontal diffusion in the unstable convective TIBL has been outlined by Lamb (1978) and Willis and Deardorff (1978) and utilized by Weil and Brower (1984). In using this approach, Misra (1980) assumes that w_* is invariant in the TIBL with respect to downwind distance from the stack. Venkatram (1977) has also indicated that w_* may not be constant downwind because of decreasing heat flux with inland distance. The assumption of constant w_* may need further field testing.

The SLDM model also makes the assumption of uniform instantaneous vertical mixing of the pollutants within the TIBL as do the other models. The two variations of the SLDM model presented here account, however, for the non-uniform mixing, one by an empirical adjustment factor and the other by incorporation of a downdraft module.

The SLDM/empirical modification assumes that at the initial plume–TIBL intersection (the point at which the lower part of the plume first intersects the TIBL interface) the rate of interception is small and similar to the final plume–TIBL interception rate (the point where the last parcel of fumigant intersects the TIBL). The rates of interception between initial and final plume–TIBL intersections are dependent on water tank empirical values for slow and fast entrainment.

The plume is expected to exhibit higher ground-level concentrations closer to the stack under fast entrainment conditions. Under slower entrainment conditions the plume concentration will be more spreadout since the fumigant is entraining over a broad TIBL interface. Under increasing thermal stratification the plume will exhibit less growth and thus have faster entrainment *in the marine air yielding higher* concentrations (Kerman, 1982). Increasing TIBL stratification, however, aids in decreasing TIBL growth and therefore decreasing entrainment. One can see how difficult it is to determine qualitatively whether fast or slow entrainment is occurring and then apply the appropriate non-dimensional t^* to represent fumigant dispersion in the convective TIBL. Kerman (1983) in fact states that the normalized entrainment rates for the NEMP experiments ranged from 0.055 to 0.21. The rates were consistently larger than those obtained by Deardorff and Willis (1982) in their water tank experiments.

Deardorff and Willis (1982) also make the assumption that entrainment is constant throughout the convective boundary layer. This assumption may not hold all the time, however, since in a TIBL the entrainment rate could vary as a function of TIBL interface structure. We have also noticed that the point of maximum concentration for the empirical modification has been pushed downwind considerably. This is shown by the example in Fig. 7 and also in Table 3 which both represent the predicted ground-level concentrations for all four models. This observation is

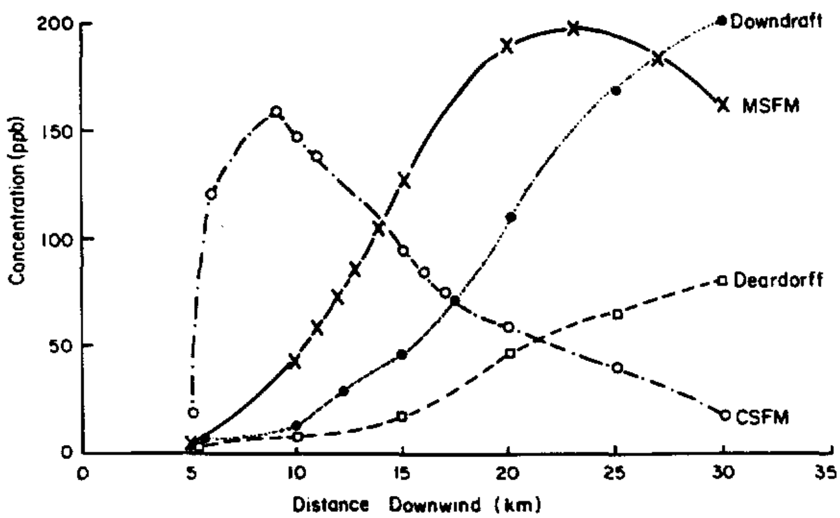

Fig. 7. Model comparison for 6 June 1978 (1600 EDT).

Table 3. Quantitative measures of coastal dispersion model performance, location of maximum concentration downwind (km)

Time (EDT)	MSFM	CSFM	Empirical modif.	Downdraft modif.	Observed
1200	25	8	30	30	17
1400	28	6	30	30	16
1500	11	7	20	30	7
1600	9	8	15	30	9
1700	13	12	25	29	10

consistent with the faster observed entrainment argument of Kerman (1983) above. The reason given by Deardorff and Willis (1983) for the displacement of the fumigation zone downwind is the representation of the initial laboratory plume as being compact at the point of TIBL interception such that:

$$\frac{\sigma_{y,s}}{h_i} \quad \text{and} \quad \frac{\sigma_{z,s}}{h_i} = 0.05 \qquad (29)$$

where $\bar{h}_i$ is the mean TIBL height where the plume initially impacts.

The NEMP plume on the average had a $\sigma_{y,s}/\bar{h}_i$ of about 1.7 and a σ_{zs} of $0.18\bar{h}_i$ based on lidar measurements of Hoff *et al.* (1982). The compact initial laboratory plume condition along with slow entrainment rates therefore produced a very dispersed plume as typified by the underprediction of concentration values.

5.4. *Sensitivity analysis of SLDM and CSFM*

The sensitivity analysis of the base models (SLDM and CSFM) examined the impact of the model input data on the model calculated concentrations. The sensitivity analysis allowed identification of the most critical model variables. An evaluation of these critical model variables should aid in the proper collection of data (i.e. what type of data is needed), quality assurance procedures and model applicability in the future.

The sensitivity analysis consisted of variations in the magnitude of each input variable. The variables considered for sensitivity analysis were:

(1) w_*/U: ratio of convective velocity to mean wind speed
(2) A: as in $h = AX^{1/2}$
(3) F_0: buoyancy flux
(4) N: Brunt–Vaisalla frequency.

The sensitivity parameters chosen for the CSFM model were based on what was unique to this version of CRSTER. Previous sensitivity studies such as Freas and Lee (1977) have shown CRSTER to be more sensitive to source parameters than to meteorological parameters. Thus, we have chosen the 'A' factor in the TIBL formulation for CSFM sensitivity analysis since this is really the only new non-CRSTER input variable.

The parameter w_* has been used as a scaling variable by several authors (see, for example, Willis and Deardorff, 1978). An increase in the value implies increased heat flux (i.e. solar radiation) which also implies increased plume instability. This means that higher values of w_*/U create more of a crosswind dispersion, thus moving the maximum concentration location closer to the stack and reducing overall ground-level concentrations. In the SLDM model, w_*/U is used in the calculation of the TIBL crosswind dispersion coefficient (σ_y).

The sensitivity analysis of w_*/U on normalized concentration C/Q appears in Fig. 8. It appears from Fig. 8 that the physical reasoning of the previous paragraph holds true. The smallest w_*/U of 0.1

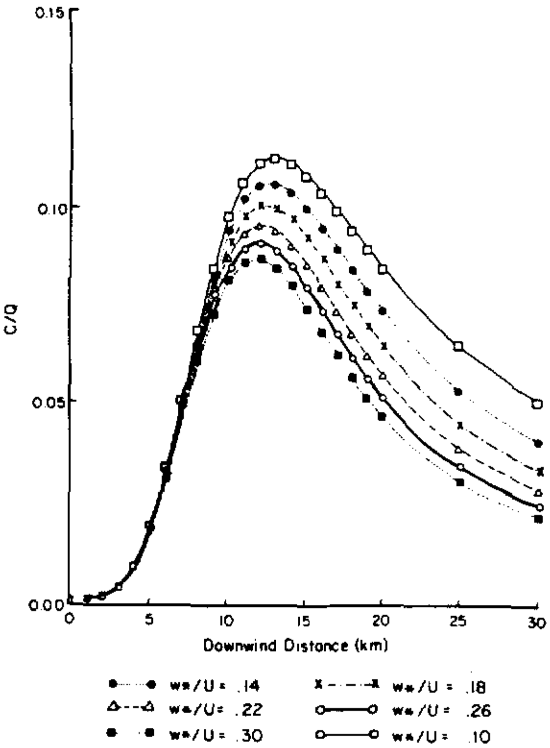

Fig. 8. Model sensitivity to the input parameter, w_*/U (normalized convective velocity).

corresponds to both the highest concentration value (C/Q) and the farthest downwind peak. This means that the plume is not as dispersed (resulting in higher ground-level concentrations) and is advected comparatively farther downwind. Consequently, higher values of w_*/U indicate lower C/Q concentrations. A gradual shift in the maximum concentration location toward the stack is also seen from Fig. 8. This confirms earlier work by Lamb (1979) who showed that maximum plume displacement and maximum plume concentration are significantly influenced by convective velocities and turbulence.

The factor 'A' takes into account all of the physics necessary for computation of the TIBL height. A sensitivity analysis on the factor 'A' therefore directly represents the effect of the TIBL height variations on concentration. Figure 9 indicates the concentration variations under different TIBL heights predicted by SLDM.

Higher values of A mean that the TIBL is steep and therefore high concentrations of pollutant should result close to the source and in a short fumigation zone. This is shown in Fig. 9 by the curve going up sharply to $C/Q = 0.14$. Lesser values of A are shown to push both the magnitude of the maximum concentration and the location further downwind. Very shallow TIBLs ($A = 2$) are shown by Fig. 9 to cause peak concentrations at greater distances. This is particularly important in strong thermally stratified onshore flow where the TIBL is suppressed and the plume will travel far downwind. This analysis supports our contention

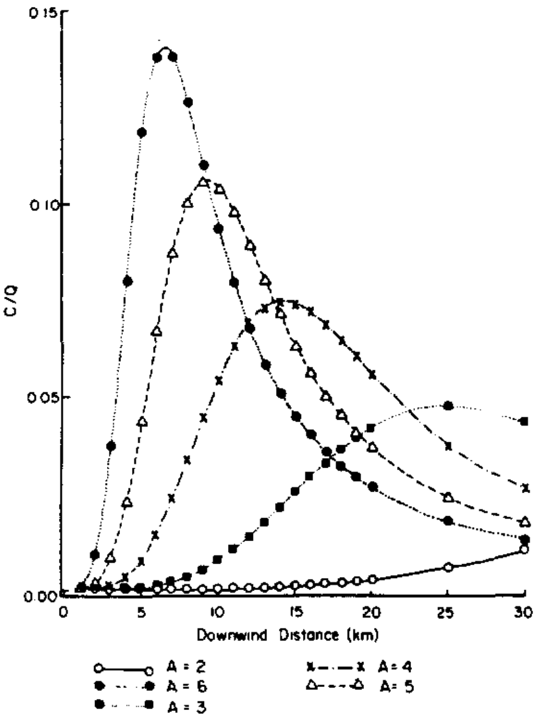

Fig. 9. Model sensitivity to the input parameter, A (TIBL parameter).

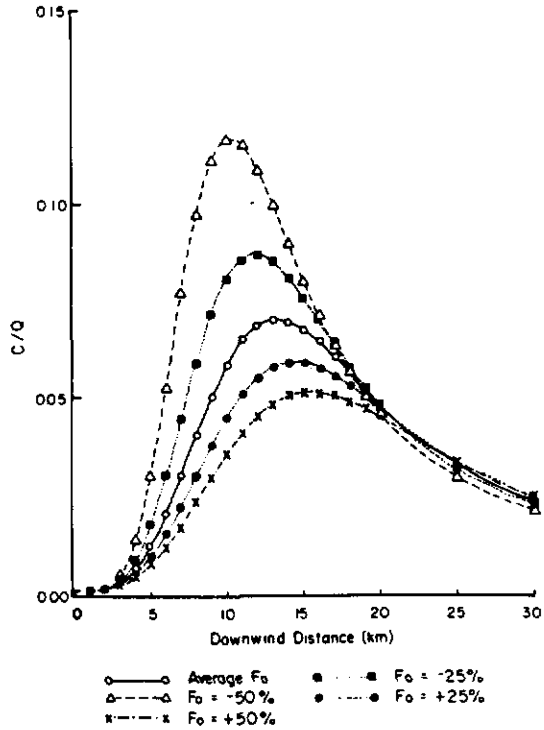

Fig. 10. Model sensitivity to the input parameter, F_0 (stack parameter).

in Section 2 that TIBL height determination is critical in coastal dispersion modeling.

The use of F_0 (plume buoyancy) allows us to implicitly draw conclusions about the behavior of the plume in the stable air since F_0 is used in the calculation of $\sigma_{y,s}$ and σ_{zs}. Figure 10 shows the concentration distribution for various F_0 values about a mean F_0 value ($585\,m^4\,s^{-1}$) determined from all NEMP hours. Lower buoyancy flux and hence less $\sigma_{y,s}$ or $\sigma_{z,s}$ indicate higher ground-level concentrations since the plume would tend to be more spread out ($\sigma_{y,s}$ and $\sigma_{z,s}$ would be greater). The point of maximum concentration is also shifted farther downwind.

The final sensitivity test involves the Brunt–Vaisalla frequency (N) which is used to quantify the stability of the stable air. The Brunt–Vaisalla frequency can be written as:

$$N = \left(\frac{g}{\theta}\frac{\partial\theta}{\partial z}\right)^{-1/2} \tag{30}$$

Figure 11 illustrates the effect of varying N on the normalized concentration. Values selected are consistent with the values observed offshore. The higher N values result in higher concentrations of fumigant closer to the source. The reason for the higher concentration values may stem from plume supression because of increased marine air stability. This means the plume has less dispersion in the stable air and thus impacts TIBL with higher concentrations. Decreasing the value of N aids in the increased (albeit small) dispersion of the plume in the stable air, thus aiding in reducing the ground-level concentrations after plume impaction. It is important to note that in the sensitivity analysis for N, we have kept the TIBL height constant. In reality, however, changing the Brunt–Vaisalla frequency will alter the stability of the marine stable air

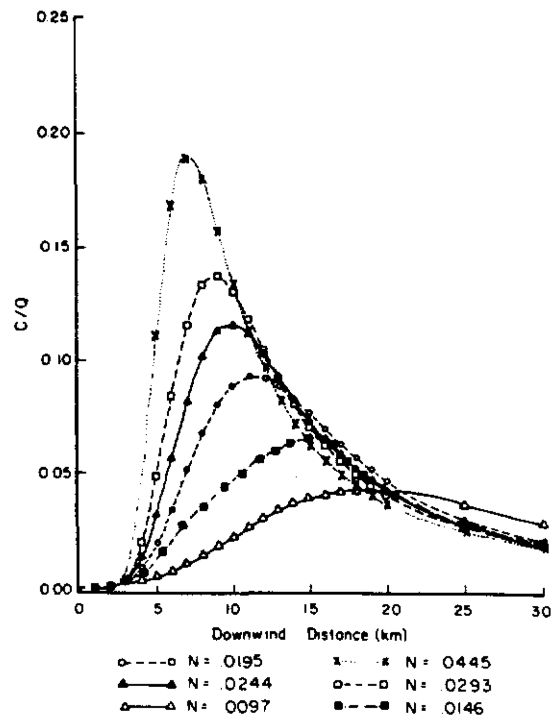

Fig. 11. Model sensitivity to the input parameter, N (Brunt–Vaisala frequency, upwind stability parameter).

and thus vary the TIBL height and in turn affect concentrations.

Comparing all the results of sensitivity analysis, the '*A*' variable used in the TIBL calculation appears to be the most sensitive variable based on the magnitude of the change in concentration and the spatial displacement of the maximum concentration location.

6. SUMMARY AND CONCLUSIONS

In this study we evaluated two coastal dispersion models (CSFM and SLDM) and two variations of SLDM (empirical and downdraft modifications). The evaluation was conducted using a comprehensive coastal dispersion data base. The specific conclusions drawn from this study are as follows:

(1) The most significant factor affecting plume dispersion in coastal areas is the shape of the TIBL. A steep TIBL produces high concentrations close to the stack while shallower TIBLs result in more diffusion farther away from the stack and consequently lesser ground-level concentrations.

(2) Based on our analysis of dispersion data from the comprehensive NEMP studies, we conclude that the SLDM model of Misra (1980) is the better base model of the two for predicting ground-level concentrations from stack releases at the shoreline. Use of empirical or downdraft modules to characterize dispersion within the TIBL did not improve predictions.

(3) The standard Pasquill–Gifford curves with Turner's correction factor does not seem appropriate to use in coastal areas. Convective velocity scaling appears to be a better method for dispersion within TIBL. Weil and Brower (1984) also arrived at the same conclusion in their study of dispersion coefficients estimated from convective velocities over land.

The plume concentration data presented by Hoff *et al.* (1982) and used in our model evaluation study points out the need for a mobile monitoring component in coastal dispersion studies. Many times during the Nanticoke study mobile monitors were able to easily track the plume while nearby fixed monitors indicated almost no concentration.

The standard air quality models do not include some of the necessary modules (i.e. TIBL, fumigation) required to handle the complexity of dispersion in coastal areas. Such models cannot therefore simulate coastal processes.

Finally, we suggest that a comprehensive study such as the one recommended by the Workshop on Coastal Transport Processes (see SethuRaman, 1983) be undertaken to supplement the results from the Nanticoke studies and to develop improved models.

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