8.1 EVALUATION OF A COMPREHENSIVE METEOROLOGICAL/DISPERSION MODEL WITH DATA FROM A SHORELINE URBAN FIELD STUDY

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1. INTRODUCTION

This paper evaluates the concentration estimates from a comprehensive model, The Air Pollution Model (TAPM), developed by Australia's CSIRO (Commonwealth Scientific and Industrial Research Organization) with observations from a field study conducted in 2005 at Wilmington, a coastal urban area located south of Los Angeles. The performance of TAPM in describing the results from the field study was compared with that of a semi-empirical dispersion model. We first provide a brief description of the field study and then present results from the two models.

2. FIELD STUDY

A field study was conducted near the Harbor Generating Station of the City of Los Angeles's Department of Water and Power (LADWP) in Wilmington, a suburb of Los Angeles in 2005. The field study focused on elevated tracer releases and was conducted between June 24th and June 28th 2005. Two types of releases were used: non-buoyant releases 3 m below the top of the 67 m stack, and releases into the buoyant stack gases. The tracer gas, sulfur hexafluoride (SF_6), was released in each experiment over periods lasting from 5 to 6 hours during each day of the four day experiment.

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Integrated box samplers were deployed along three arcs with distances of 1000 m, 3000 m and 5000 m north of the source. A minisodar, two sonic anemometers, with their sensors at heights of 3 and 6 meters, soil moisture and surface temperature sensors, temperature and relative humidity measurement systems were placed near the western fence line of the power plant, approximately 100 meters away from the plant stacks. A second minisodar, a three-axis sonic anemometer and a remote sensing microwave temperature profiler were located 4 km downwind of the release.

3. TAPM

3.1 TAPM Model Description

TAPM is a three-dimensional prognostic meteorological and air pollution model developed by the CSIRO (Commonwealth Scientific and Industrial Research Organization) Atmospheric Research (Hurley et al. 2005).

The meteorological component of TAPM solves the momentum equations for horizontal wind components, the incompressible continuity equation for the vertical velocity in terrain following coordinate system, and scalar equations for potential virtual temperature, specific humidity of water vapor, cloud water and rain water. Wind observations can be optionally assimilated into the momentum equations as nudging terms. Pressure is determined from the sum of hydrostatic and optional non-hydrostatic components. A Poisson equation is solved for the non-hydrostatic component. Explicit cloud microphysical processes are included in the model.

The air pollution component of TAPM uses the predicted meteorology and turbulence from the meteorological component and it consists of four modules. The Eulerian Grid Module solves prognostic equations for the mean and variance of concentration; The Lagrangian Particle Module can represent near-source dispersion more accurately; The Plume Rise Module is used to account for plume momentum and buoyancy effects for point sources; The Building Wake Module allows plume rise and dispersion to include wake effects on meteorology and turbulence.

3.2 Model Setup

TAPM model performance was evaluated using Wilmington 2005 study for elevated releases.

(a) Meteorology Grid

TAPM (version 3.0) was run with four nested grid domains at 30, 7.5, 2, 0.5 km resolution for meteorology (30×30 grid points). The grid center is 33°47.5′ N, 118°16′ W, which is equivalent to (382738m, 3739778m) in the Universal Transverse Mercator (UTM) coordinate system, and is almost the mid-point between LADWP site and JWPCP site. 25 vertical grid levels were used, and the lowest ten of these levels were 10, 25, 50,100, 150, 200, 250, 300, 400, and 500 m, with the highest level at 8000 m. Modifications are made to the TAPM land-use database to account for the existence of several canals in this area.

Deep soil moisture content is another important input to the TAPM model. Results from sensitivity tests indicated an optimum value of 0.25 for deep soil moisture.

(b) Wind Assimilation

Three cases of wind assimilation were used in the simulations: (1) without assimilation, (2) wind information from only the LADWP (the release site at Los Angeles's Department of Water and Power) site, and (3) wind measurements from both the LADWP and JWPCP (the 4km downwind site at Los Angeles County Sanitation District's Joint Water Pollution Control Plant) sites. Model estimates of meteorology as well as concentration are compared with corresponding observations for these three cases.

The wind speed and direction observed by the sonic anemometers were assimilated into the lowest model level at 10 m at the corresponding co-ordinates in TAPM. The observed wind speed at the observed height was extrapolated to the next five model levels - 25, 50, 100, 150 and 200 m - using similarity relationships by van Ulden and Holtslag (1985). The wind directions at 25 m level were set to be the same as those at 10 m. The wind directions for the next four vertical levels were estimated from sodar observations at LADWP site and JWPCP site.

(c) Dispersion Simulation

The tracer particles were tracked in a domain of 5 km by 5 km covering Wilmington using a 111 by 111 grid system with a uniform spacing of 50 m. The SW corner of the grid system is (379988 m, 3737028 m) in UTM coordinates.

The tracer releases during the Wilmington 2005 field study consisted of an elevated buoyant release and a non-buoyant release. For the elevated non-buoyant release, the source height was set to be 64 m, the source radius was 0.02 m, the exit velocity was 0.01 m/s, and the exit temperature was 293 K; for the elevated buoyant release, the source height was set to be 67 m, the source radius was 2.36 m, the exit velocity was 22.86 m/s, and the exit temperature was 458.15 K. The emission rate was 4.4 g/s (16 kg/hr) for most hours of the field study, and was 2.2 g/s (8 kg/hr) for some of the early hours.

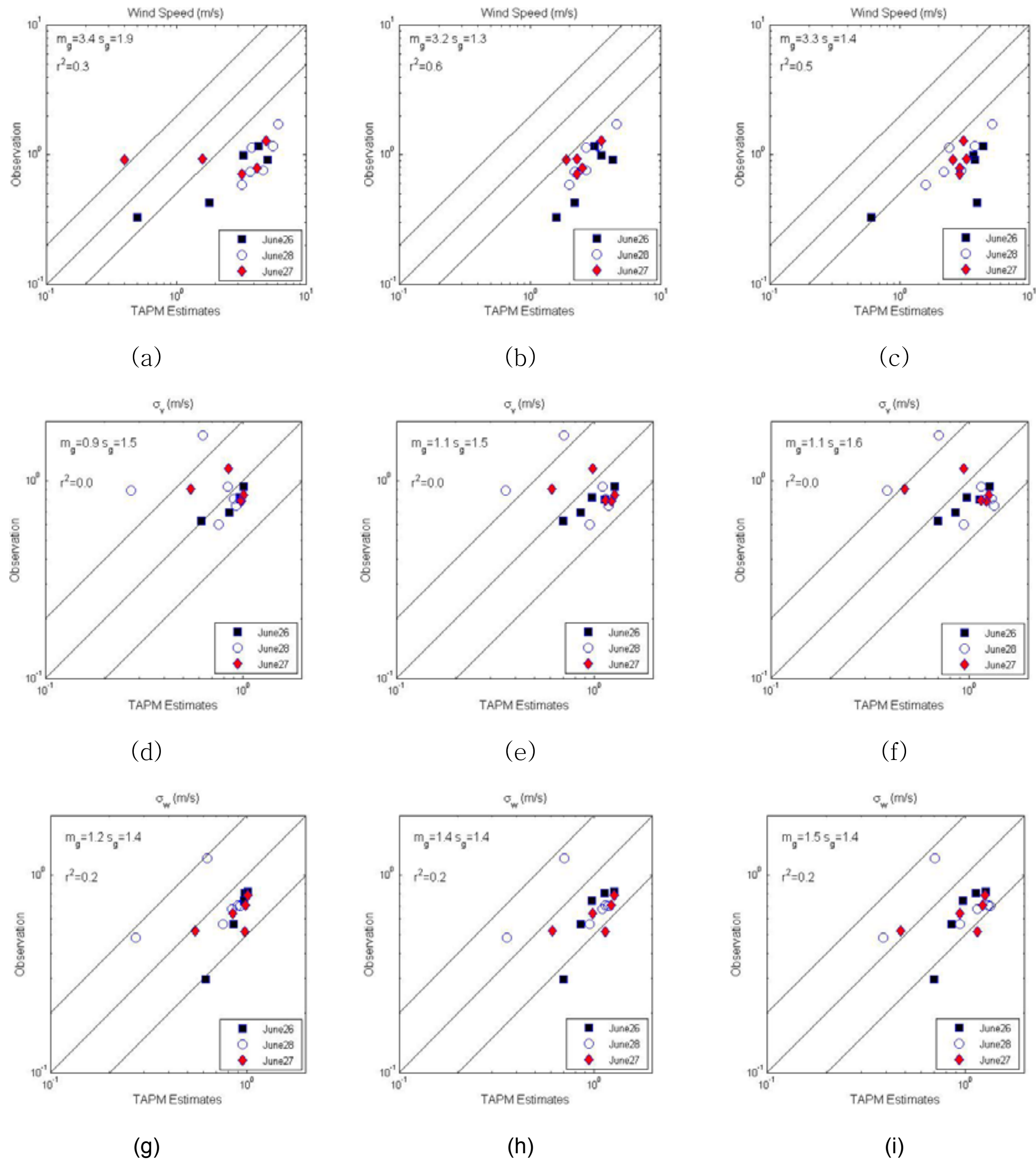


Figure 1. Comparisons of mean wind speeds, horizontal turbulent velocities, vertical turbulent velocities at JWPCP site estimated by TAPM with observed values from Wilmington 2005 field experiment. (a), (d) and (g) are without wind assimilation; (b), (e) and (h) are with wind assimilated at LADWP site only; (c), (f) and (i) are with wind assimilated at both LADWP and JWPCP sites.

3.3 Evaluation of Meteorological Outputs from TAPM

With the measured meteorological data, we can evaluate TAPM model by comparing the estimates of meteorological data with measured data. Model performance is quantified in terms of the geometric mean, m_g, of the ratio of the estimated, C_p, to observed data, C_o:

$$m_{\mathrm{g}} = \exp\left(\mathrm{mean}\left(\varepsilon\right)\right) \quad (1)$$

where

$$\varepsilon = \log\left(\frac{C_{\mathrm{p}}}{C_{\mathrm{o}}}\right)$$

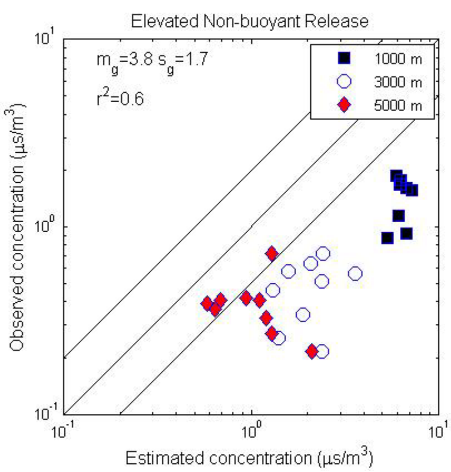
and the spread of observations about a model estimate is quantified using the geometric standard deviation, s_g,

$$s_g = \exp(\text{standard deviation of } \varepsilon) \quad (2)$$

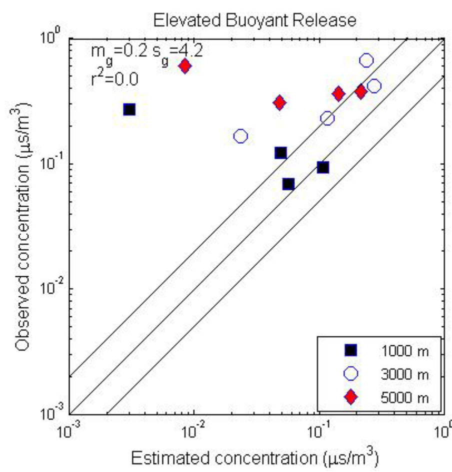
Then if the observed data are log-normally distributed about the model estimate the 95% confidence of the ratio of the observed to the estimated data is given by the interval $m_g s_g^{1.96}$ to $m_g s_g^{-1.96}$. r^2 is the correlation coefficient between the logarithmic values of C_o and C_p.

Figure 1 compares the horizontal wind speeds, horizontal and vertical turbulent velocities estimated by TAPM at the JWPCP site with the corresponding observations during the Wilmington 2005 field study. The estimates for wind speed are well correlated with the observed values, but they are overestimated by factors of 3 to 4. Assimilation of local wind information decreases the degree of overestimation of the wind speed. The standard deviation of the vertical velocity fluctuation, σ_w, is overestimated by almost a factor of two by TAPM, presumably because it overestimates the mean wind speeds. Assimilation of winds appears to increase the overestimation slightly. TAPM produces acceptable estimates of σ_v (the standard deviation of the horizontal velocity fluctuation) for cases with and without wind assimilation; the model estimates show little bias and are within a factor of two of the observations.

Generally speaking, the estimation of meteorological parameters is better when local wind measurements are assimilated than otherwise. But it is difficult to distinguish between results from the two assimilation cases: LADWP site only and both the LADWP and JWPCP sites.



(a)



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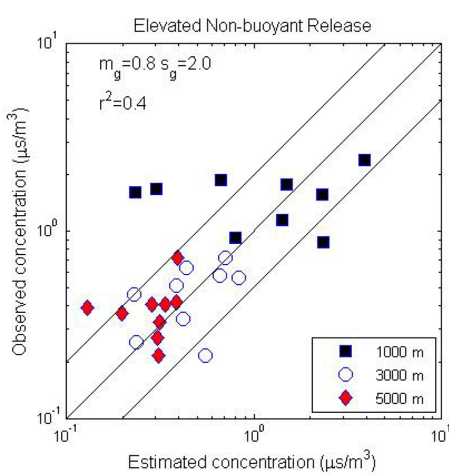

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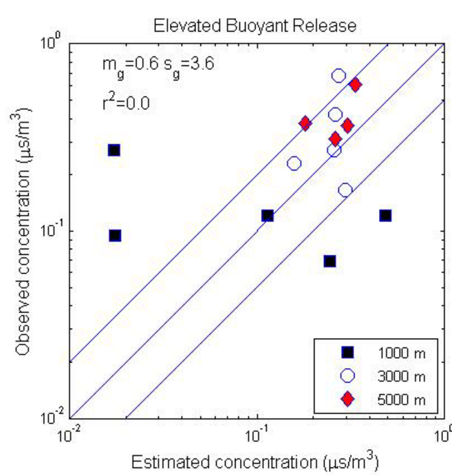

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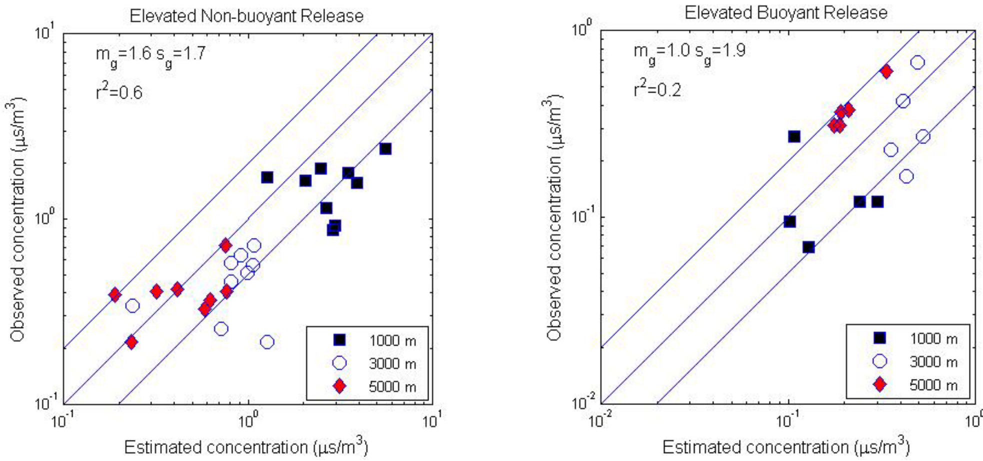


(e) (f)

Figure 2. Comparison of model estimated arc maximum concentrations and observations. Elevated non-buoyant releases on the left panel include the scenarios on June 26 and 28 2005, and elevated buoyant releases on the right panel correspond to the cases on June 27 2005. (a) and (b), TAPM (without assimilation); (c) and (d), TAPM (LADWP assimilated); (e) and (f) TAPM (LADWP+JWPCP assimilated)

3.4 Evaluation of Concentration Outputs from TAPM

The observed arc maximum concentrations on the three arcs at 1000, 3000 and 5000 m are plotted against estimates from TAPM in Figure 2.

From Figure 2, we can see that for elevated non-buoyant releases, TAPM overestimates all the arc maximum concentrations for all the three arcs when wind is not assimilated. But the correlation between the estimated and observed concentrations is fine. And TAPM yields acceptable estimates of most of the arc maximum concentrations when the wind is assimilated at the LADWP site or at both LADWP and JWPCP sites.

However, for the elevated buoyant releases, TAPM estimated arc maximum concentrations are uncorrelated with observations when wind is not assimilated and when wind is assimilated only from the LADWP site. Model performance improves to some extent when wind is assimilated from both sites, although the arc maximum concentration is still overestimated at the 1000 m arc and underestimated at the 5000 m arc.

4. SEMI-EMPIRICAL MODEL

The performance of TAPM was compared with that of a semi-empirical dispersion model.

4.1 Semi-empirical Model Description

The dispersion model used here to interpret the field data is similar to that developed by Van Dop et al. (1979), and improved by Misra (1980). We have modified the model to incorporate the measurements of turbulence made in the Wilmington experiment.

Misra's (1980) model is based on the following physical picture. As the elevated plume is transported above the internal boundary layer, it grows both horizontally and vertically due to atmospheric turbulence and turbulence generated by plume buoyancy. Because atmospheric turbulence is small above the Thermal Internal Boundary Layer (TIBL), plume buoyancy generates most of the plume growth. This growing plume is entrained by the TIBL, whose height increases with distance from the shoreline (Figure 3). The entrained plume material is rapidly mixed to ground-level by the vigorous convective motions within the internal boundary layer.

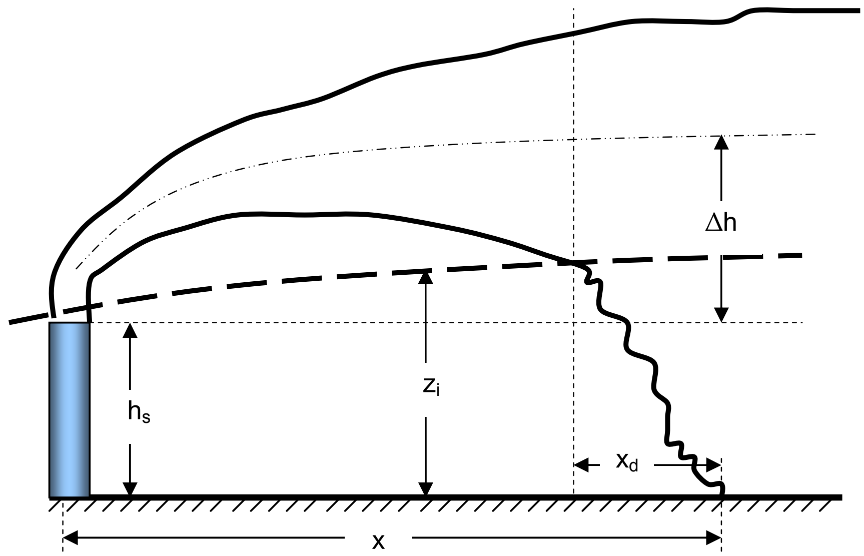


Figure 3. Entrainment of plume by growing internal boundary layer.

The gradual entrainment of the elevated plume by the internal boundary layer is modeled by Misra (1980) as a series of point sources whose strength depends on the rate of entrainment by the TIBL and the vertical growth of the plume. Assuming that the entrained plume material is instantaneously mixed through the depth of the TIBL, the ground-level concentration is given by the sum of the contributions of all the upwind point sources. The expression for the centerline ground-level concentration is given by Misra (1980):

$$C(x,0,0) = \frac{Q}{\sqrt{2}\pi U z_{\mathrm{i}}} \int_{-\infty}^{p} \frac{1}{\sigma_{\mathrm{yc}}} \exp\left(-p^2\right) dp \qquad (3)$$

where Q is the release rate; and z_i is the height of the TIBL at the distance x, which will be discussed in detail later. The integrating variable p is related to x', the location of the point source, through

$$p = \frac{\left(z_{\mathrm{i}}\left(x'\right) - h_{\mathrm{e}}\right)}{\sqrt{2}\sigma_{\mathrm{zs}}\left(x'\right)} \qquad (4)$$

where h_e is the effective stack height, and σ_{zs} is the vertical plume spread above the internal boundary layer. The horizontal plume spread in Eq. (3) is given by

$$\sigma_{\mathrm{yc}}^2 = \sigma_{\mathrm{ys}}^2\left(x'\right) + \sigma_{\mathrm{yu}}^2\left(x - x'\right) \qquad (5)$$

In Eq. (5), σ_{ys} is the horizontal spread in the layer above the internal boundary layer, and σ_{yu} is the horizontal spread within the TIBL. Note that the effective horizontal plume spread combines two spreads; the plume spread in the layer above the TIBL over the distance 0 to x', and then in the TIBL over the distance (x - x').

Sensitivity studies with the model suggested that best results were obtained when σ_v above the TIBL was taken to be same value as that within the TIBL. This allows us to combine the two terms in Eq. (5) to obtain an expression for the horizontal plume spread as a combination of that caused by turbulence and that due to plume buoyancy:

$$\sigma_{\mathrm{yc}} = \sqrt{\sigma_{\mathrm{y}}{}^2 + \sigma_{\mathrm{s}}^2} \qquad (6)$$

where σ_y is given is the spread caused by atmospheric turbulence,

$$\sigma_y = \frac{i_y x}{\left(1 + x/L_y\right)^{1/2}} \tag{7}$$

The length scale, L_y, was taken to be 2500 m, a value suggested by Briggs (1973) for use in urban areas on the basis of his analysis of the St. Louis experiment (McElroy and Pooler, 1968). The term σ_s is the plume buoyancy induced spread, which is discussed later. It turns out that Eq. (7) is consistent with the horizontal spreads derived from data collected in the 2005 experiments.

The vertical spread, σ_{zs}, is taken to be

$$\sigma_{zs} = \sqrt{\left(\frac{\sigma_{ws} x}{U}\right)^2 + \sigma_s^2} \tag{8}$$

where the vertical turbulence, σ_{ws} is taken to be a nominal value of 0.001 times the value in the internal boundary layer.

Because the horizontal plume spread is not a function of p, as assumed in Eq. (7), we can take it outside the integral in Eq. (3) to obtain

$$C\left(x,0,0\right) = \frac{\text{frac}}{\sqrt{2\pi} U \sigma_{yc} z_i} \tag{9}$$

where frac, the fraction of the plume entrained into the TIBL, is

$$\text{frac} = \frac{1}{2}\left(1\text{-erf}\left(\left(\frac{z_i - h_e}{\sqrt{2}\sigma_{zs}}\right)\right)\right) \tag{10}$$

where erf is the error function. In Eq. (10), the effective stack height is

$$h_e = h_s + \Delta h \tag{11}$$

where h_s is the physical stack and plume rise is given by:

$$\Delta h = \min\left(1.6\frac{F_b^{1/3}}{U} x^{2/3}, 2.6\left(\frac{F_b}{Us}\right)^{1/3}\right) \tag{12}$$

where the buoyancy parameter F_b is defined as

$$F_b = gV_s\left(\frac{D_s}{2}\right)^2 \frac{T_s - T}{T_s} \tag{13}$$

where V_s, T_s and D_s are the exhaust velocity, temperature and diameter of the stack; T is the ambient temperature. The stability parameter, s, is defined as

$$s = \frac{g}{T}\frac{d\theta}{dz} \tag{14}$$

Self-induced plume spread is related to plume rise through

$$\sigma_s = \frac{\beta \Delta h}{\sqrt{2}} \tag{15}$$

where the entrainment coefficient $\beta = 0.6$.

The concentration at x is determined by the material entrained at upwind distances x'<x. But only a fraction of the material that is entrained into the TIBL is well mixed through the boundary layer depth at the distance x. We need to account for this in Eq. (9), which assumes that the material is well mixed through z_i. To do so, we first calculate the distance x_d required for a release to become well mixed by the time it reaches x (Figure 3). This distance is given by

$$\sqrt{\frac{2}{\pi}} z_i = \frac{\sigma_w x_d}{U} \tag{16}$$

where z_i is the boundary layer height at x. Then, frac in Eq. (10) is evaluated at the reduced distance (x – xd). Without this modification, the model proposed by Misra (1980) overestimates the concentrations for the elevated release.

The thermal internal boundary height, z_i, is computed using the expression (Venkatram 1977):

$$z_i = a\left(\frac{Q_o(x + x_o)}{U\gamma}\right)^{1/2} \tag{17}$$

where Q_o is the average kinematic heat flux over land, x is the distance from the shoreline, U is the boundary layer averaged wind speed, and γ is the potential temperature gradient above the TIBL. The parameter x_o is the distance of the effective shoreline from the release, which cannot be objectively determined in view of the complicated geometry of the coastline. Taking x_o = 100 m yielded the best agreement between modeled concentrations and observations corresponding to elevated releases. The parameter, a, is empirically determined to be 2.

The next section describes results from the application of the model to describe the concentration observations described earlier. Note that the model applies to both buoyant and non-buoyant releases. The buoyancy parameter, F_b, is set to zero and h_s = 64 m for the non-buoyant release.

4.2 Evaluation of Concentration Outputs from Semi-empirical Model

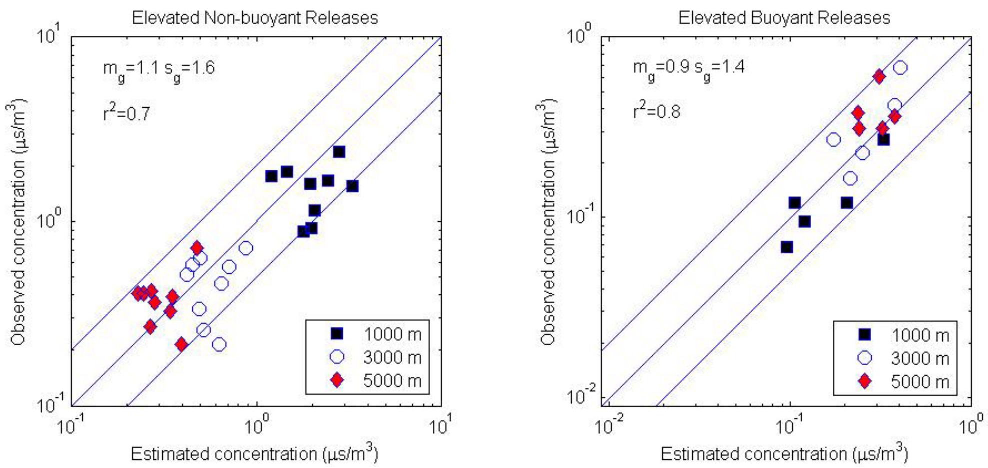


Figure 4. Comparison of measured arc maximum concentrations with model results for non-buoyant (left) and buoyant (right) releases for Wilmington 2005 study. The length L_y in Eq. (7) is 2500 m in the left panel but is reduced to 1000 m in the right panel.

Figure 4 compares observed arc maximum concentrations with model estimates obtained using onsite meteorological inputs. The left panel corresponds to elevated non-buoyant releases. Most of the model estimates are within a factor of two of the observed values, and the model explains 70% of the variance of the observations. The right panel indicates that model performance for elevated buoyant releases is also adequate, with all the observations lying within a factor of two of the model estimates; the model explains 80% of the observed variance.

We can now compare the performance of TAPM (Figure 2) with that of the semi-empirical model (Figure 4). For the non-buoyant releases, TAPM outputs for wind assimilated cases are comparable to those from the semi-empirical model. However, for the buoyant releases, TAPM did not provide adequate concentration estimates even when wind is assimilated at both LADWP and JWPCP sites.

5. INVESTIGATION ON TAPM PERFORMANCE

In this section, we investigated further on the reason why TAPM doesn't give adequate results, especially for elevated buoyant releases.

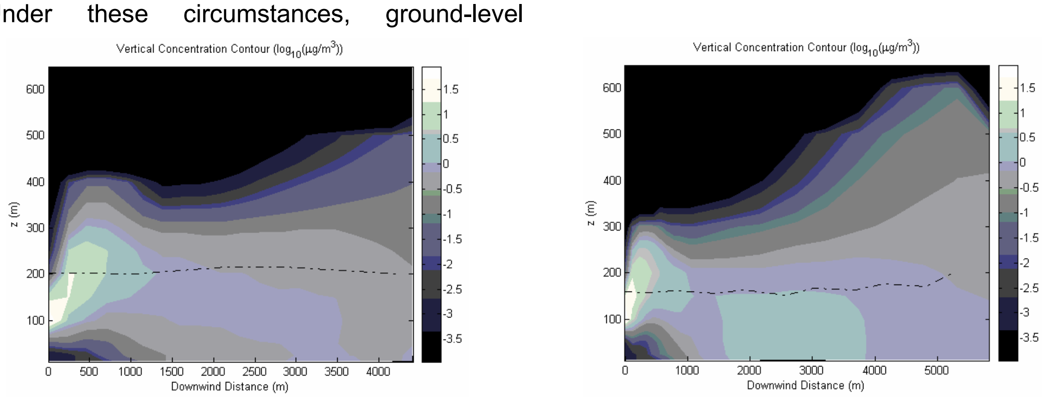
5.1 Mixed Layer Height from TAPM

In Figure 5, we plotted vertical cross-sectional concentration contours predicted by TAPM along with the mixed layer heights given by TAPM. It is noticeable that the plume is entrained into the boundary layer and mixed down to the ground. However, the boundary layer does not grow with downwind distance from the coastline; it remains at a single height. Thus TAPM is unable to simulate a fundamental feature of boundary layer behavior at the land-water interface.

The incorrect behavior of the thermal boundary layer does not play a major role for the non-buoyant elevated release because it behaves like a ground-level source. The mixed layer height only limits the vertical spread at the downwind distance of 5000 m.

When the elevated release is buoyant, the effective release height is over 400 m, which is close to the maximum internal boundary layer. Under these circumstances, ground-level concentrations are governed by the entrainment of the elevated plume by the growing TIBL. Thus, errors in modeling the growth of the TIBL affect ground-level concentrations. And, it is not surprising that TAPM was less successful for elevate buoyant releases. The arc maximum concentration is overestimated at the 1000 m arc and underestimated at the 5000 m arc by TAPM. This behavior is consistent with the incorrectly predicted constant boundary layer height, which entrains too much plume near the source and inadequate amount of plume at large downwind distances.

For both elevated non-buoyant and buoyant releases, concentrations estimates from the semi-empirical dispersion model compare better with observed arc maximum concentration than do TAPM estimates. This is due to the more realistic specification of the TIBL height, the alignment of boundary layer growth with wind direction, and the use of onsite meteorological measurements in the Wilmington model.



(a) (b)

Figure 5. Vertical cross section concentration contours and mixed layer heights at 12:00 pm June 27, 2005. (a) corresponds to LADWP assimilated case; (b) corresponds to LADWP+JWPCP assimilated case. Note that concentration contours use a logarithmic scale with grayscale effect. The light colors represent higher concentrations and the dark colors correspond to lower concentrations.

5.2 Meteorological Outputs from TAPM

We also investigated the reason why TAPM overestimated concentrations for the non-buoyant releases.

We noticed that the non-buoyant elevated release is rapidly brought down to the ground by the turbulence in the boundary layer, which is higher than the release height. Under these conditions, the elevated release behaves as a ground-level source and the centerline concentrations is inversely proportional to the dilution velocity (Venkatram et al., 2004) given by $\sigma_w\sigma_v/U$.

As we have seen in Figure 1, when compared with observations from the

Wilmington 2005 field study, TAPM overestimates the mean wind speeds by factors of 3 to 4, and overestimates σ_w by almost a factor of 2; TAPM wind speeds are brought closer to lower observed wind speeds through assimilation. TAPM estimates of σ_v show little bias when compared with observations, and these estimates are within a factor of two of the observations.

The errors in TAPM estimates of meteorological variables lead to underestimation of the dilution velocity and thus the overestimation of ground-level concentrations for the non-buoyant elevated release, when wind is not assimilated into the model. This overestimation is reduced when the TAPM wind speeds are brought closer to the lower observed winds through assimilation.

5.3 Downwash Mixing of TAPM

When TAPM's particle model is used to estimate concentrations, concentrations close to the source for the non-buoyant elevated release are overestimated presumably because the incorrectly large mixing near the source brings the plume down too close to the source, and the effective ground-level source is governed by the underestimated dilution velocity. The rapid downward mixing is likely to be the cause of the overestimation of arc maximum concentrations close to the source when the release is buoyant. The reasons for underestimation at the furthest arcs are not clear, although there is some indication that wind direction could play a role here. More detailed investigation of the causes for TAPM's performance in explaining the Wilmington observations requires extensive sensitivity studies combined with reformulation of the model.

6. CONCLUSIONS

This paper examines the feasibility of using a comprehensive model, such as TAPM, to model short range dispersion in coastal urban areas. TAPM yields acceptable concentration estimates for non-buoyant releases, but behaves poorly for buoyant releases. Wind assimilation can improve the model performance. The semi-empirical dispersion model gives better results because it uses onsite wind measurement as inputs and it accounts for the growth of the TIBL using a simple model. The inability of TAPM in simulating the growth of TIBL with distance from the shoreline might explain the poor results for elevated buoyant releases. Other factors, such as the overestimation of wind speed and rapid downwash mixing, also contribute to the performance of TAPM.

ACKNOWLEDGEMENT

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