Peak Concentrations and Plume Diffusion in the Atmospheric Surface Layer

Holly G. Peterson, Environmental Engineering Department, Montana Tech of The University of Montana, Butte, MT 59701
Tina Donovan, Environmental Engineering Department, Montana Tech of The University of Montana, Butte, MT 59701
Susan M. O'Neill, USDA Forest Service, Seattle, WA 98103
Brian K. Lamb, Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164-2910

Abstract

To improve our understanding of pollutant behavior in the atmosphere, tracer experiments were conducted in 1997 at a field site near Galen, Montana. We developed an empirical method to estimate instantaneous plume spread as a function of standard wind statistics and travel time. Predicted diffusion coefficients are within a factor of 2, or better, of observed values for the 1997 data, and the average predicted-to-observed ratio was 1.03 for an expanded dataset of 97 samples representing a range of terrain types, meteorological conditions, and travel times. The 1997 field data are also used to test a meandering plume model, and modeled time series are similar to observed data including fluctuation statistics such as concentration mean, intensity, intermittency, and peak-to-mean ratio. Finally, we propose a simple approach to predict normalized peak concentrations for ground-level sources. The technique is shown to be realistic, yet conservative, with an average predicted-to-observed ratio of 1.90 for a variety of field studies.

Key words: concentration fluctuations, diffusion modeling, peak concentrations, plume spread, tracer experiments

Introduction

Peak concentrations are important when addressing short-term exposures to toxic air pollutants and to chemical agents such as nerve gases. Air diffusion programs such as the Industrial Source Complex (ISC) or SCREEN models predict 1-hr average concentrations downwind of contaminant sources. Field studies, however, using gaseous tracers have shown that concentration fluctuates dramatically at fixed receptors during 1-hr periods under all stability conditions, and peak concentrations may be many times higher than average concentrations. Because acute exposures may pose health risks for exposure to toxic or hazardous gases above threshold values, dispersion models should be capable of addressing variability or peak concentrations on time scales similar to human breathing rates.

In this paper we address recent efforts to investigate and model concentration fluctuations and peak concentrations from surface-level, pollutant plumes. The goals of the research are to 1) improve our understanding of plume behavior in the atmosphere, and 2) develop a simple approach of incorporating instantaneous exposure statistics into the regulatory modeling arena. Here, we provide background information and describe recent experiments using tracer technologies to obtain concentration fluctuation data. We analyzed the tracer data in terms of instantaneous plume spread and concentration fluctuation statistics, and examined performance and uncertainties of a meandering plume model. Finally, we used our field data to test a simple method of predicting normalized peak concentrations.

BACKGROUND

Average plume dispersion is a function of two components: diffusion relative to the instantaneous plume centerline, and meander relative to the average plume centerline (Gifford 1959). In general, small-scale eddies are responsible for diffusion whereas large-scale atmospheric motions cause the plume to meander. The separation between large and small wind features changes with plume travel time. For example, at distances close to the source, where the plume is narrow, meandering motions dominate plume behavior. At distances farther from the source, motions that previously contributed to meander, promote internal mixing.

Both diffusion and meander affect the nature of instantaneous pollutant exposure at a fixed receptor located downwind of a source. Specifically, diffusion determines the magnitude of concentrations at a specific downwind distance while meander is responsible for intermittent exposure as the plume wavers back-and-forth in the wind.

Peak concentrations in a pollutant plume are a function of instantaneous plume spread whereas mean concentrations are due to both plume meander and spread. As early as 1959, Gifford derived peak-to-mean ratio (P/M) at the centerline of a time-averaged plume (Gifford 1959) as $P/M = (Y^2 + D^2)(Y^2)^{-1}$. In this equation, Y^2 represents the mean square diffusion of a plume element relative to the centroid; D^2 represents the mean square meander of the plume centroid about the mean plume axis; and $Y^2 + D^2$ corresponds to the average spread of the plume. Gifford's peak-to-mean approach was never formulated into a regulatory tool, and until recently, few data were available regarding concentration peaks and relative diffusion because of a lack of fast-response instrumentation.

During the past two decades, however, a variety of methods have been utilized to study concentration fluctuations with fast-response equipment. For example, Hanna (1984) and Dinar et al. (1988) conducted oil fog experiments and monitored smoke concentrations at fixed receptors located downwind of the source. Sawford (1985) analyzed plumes of smoke and sulfur hexafluoride (SF_6) while Jones (1983) measured ionized air concentrations. Lewellen and Sykes (1986) and Jørgensen and Mikkelsen (1993) used lidar to remotely resolve fluctuations of particle plumes, whereas Mylne (1992), Mylne and Mason (1991), and Yee et al. (1993, 1994) released propylene gas in conjunction with high-resolution photoionization detectors.

In addition, fast-response SF_6 analyzers developed by Benner and Lamb (1985) were used during a series of novel field studies to study concentration fluctuations and plume spread. Specific campaigns included the Washington Wheatfield Study (WWS) and the Washington Desert Study (WDS) of Peterson et al. (1990) and Peterson and Lamb (1992), the Energy Resources Conservation Board (ERCB) experiments described in Peterson and Lamb (1995) and Joshi (1998), and the Galen and Boardman tests by Peterson et al. (1999). In all cases, we released SF_6 at a constant rate near the surface and measured plume concentrations at fixed points and along crosswind traverses with sampling rates between 1 and 20 Hz. Local winds were monitored with fast-response anemometers. These studies represented a wide range of conditions in the intermountain and northwest regions. Surface terrain included flat fields, forest canopies, and rolling hills; average wind speeds varied between 0.8 and 11.6 ms^{-1}; standard deviation of horizontal and vertical wind angles ranged 3-79° and 1-25°, respectively; stability categories A-G were observed; and source-to-receptor distances were between 100 and 1000 m. The remainder of this paper addresses an additional set of experiments performed near Galen, Montana, during August of 1997 in terms of plume diffusion, concentration fluctuations, and peak concentrations.

FIELD EXPERIMENTS

To investigate instantaneous behavior of surface-level plumes, Donovan (1998) conducted a tracer campaign in August of 1997 amid a flat, rural valley located east of Interstate-90, just beyond the Galen exit, in southwest Montana. An abandoned railroad bed running approximately north-south and a rural road running east-west divided the field site. Grasses and weeds, about 0.1-0.3 m in height, were the dominant vegetation. Figure 1 depicts the general layout of the experiments, including the SF_6 release system, the analyzer, and a wind sensor.

The tracer release system consisted of a pressurized tank of sulfur hexafluoride gas. The SF_6 from the tank was released at a constant rate through a calibrated rotameter and through 0.95 cm O.D. tubing with an exit height of approximately 1.5 m.

We measured SF_6 plume concentrations with a Rydock Scientific Microanalyzer at fixed locations with source-to-receptor distances ranging from 324-748 m. The analyzer was based on the electron capture detection (ECD) design of Benner and Lamb (1985) with a response time of 0.6 s, and a detection limit near 30 part-per-trillion (ppt) by volume. We performed calibrations at the beginning and end of each test using zero air and Scott-Marin certified gas standards, and we collected concentration data at a rate of 1 Hz.

The wind sensor for the Galen study was an R.M. Young uvw anemometer positioned at a height of 3.1 m. In this campaign, the uvw anemometer was oriented with the u-propeller facing east, the v-propeller facing north, and the w-propeller directed upward. Wind vector data were collected at a rate of 1 Hz, and ambient temperatures and pressures were recorded at the onset of each test using a digital temperature probe and barometer.

Table 1 summarizes conditions for eight tracer experiments performed at Galen during late afternoon/evening hours. Each test was approximately one hour in duration. Average wind speeds ranged 1.1 to 4.4 m s^{-1}; standard deviation of horizontal and vertical wind fluctuations varied 11-56° and 4-7°, respectively; and stability categories were extremely unstable through neutral (A-D) based on the Sigma-A method (USEPA 1987).

Figure 2 shows wind speed and wind direction time series for one representative experiment, Test S808d. The statistics for this case included an average wind speed of 4 ms^{-1}, an average wind direction of 303°, and a standard deviation for horizontal wind angle of 19°.

RESULTS

Instantaneous Plume Coefficients

Plume spread, on either an average or instantaneous time frame, is assumed to be a function of travel time and atmospheric turbulence. As presented by Draxler (1976) and others, "average" dispersion coefficients should be equal to

$$\sigma_y \cong \sigma_\theta X f_1 \qquad (1)$$

and

$$\sigma_z \cong \sigma_\phi X f_2 \qquad (2)$$

where σ_y and σ_z are standard deviations of the average horizontal and vertical concentration distributions (with units of m), respectively; σ_θ and σ_ϕ are standard deviations of the azimuth and elevation wind angles (in units of radians); X is downwind distance; and f_1 and f_2 are unitless decay functions. For the decay functions, Draxler (1976) incorporated travel time (t) into the following simple equation for ground sources:

$$f_1 \text{ or } f_2 = [1+0.9(t/T_o)^{0.5}]^{-1} \qquad (3)$$

with T_o equal to 300 s for f_1, and T_o equal to 100 s or 50 s for f_2 under non-stable or stable conditions, respectively.

While instantaneous plumes are known to be narrower than time-averaged counterparts, a similar approach can be developed to predict the "relative" diffusion, or spread relative to the plume axis. In particular, the standard deviations of the horizontal and vertical instantaneous

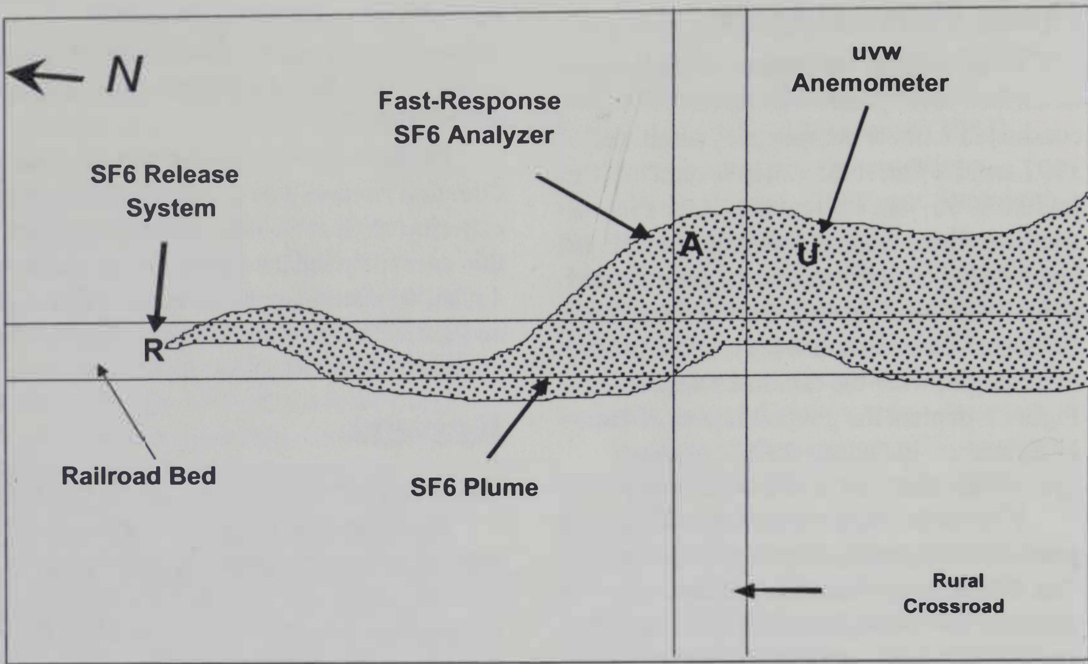

Figure 1. Example experimental setup during Galen tracer experiments.

concentration distributions, σ_{yi} and σ_{zi}, may be written as

$$\sigma_{yi} \cong \sigma_\theta X f_{1i} \quad (4)$$

and

$$\sigma_{zi} \cong \sigma_\phi X f_{2i} \quad (5)$$

where f_{1i} and f_{2i} are again decay coefficients. Equations (4) and (5) are subsequently combined to estimate to the relative diffusion coefficient, σ_i, as

$$\sigma_i = (\sigma_{yi}\, \sigma_{zi})^{0.5} \cong (\sigma_\theta \sigma_\phi)^{0.5} X (f_{1i}\, f_{2i})^{0.5} \quad (6)$$

with $f_{1i}\, f_{2i}$ likely to be some function of travel time.

As shown in Table 2, diffusion coefficients for the Galen campaign range from 15.7 to 31.5 m, and travel time (t), as inferred from $t = X U^{-1}$, varies between 94 and 453 s. Values of $(f_{1i}\, f_{2i})^{0.5}$ for these experiments vary between 0.09 and 0.43. The data are plotted against travel time (Fig. 3), and curve-fitting the field data results in a "best-fit" equation of

$$(f_{1i}\, f_{2i})^{0.5} = -0.1078 \ln(t) + 0.7898 \quad (7)$$

with an R correlation factor of 0.5858. Also shown on the graph is the curve for Draxler's time-averaged function from Equation (3) for surface plumes under nonstable conditions. Overall, for this range of experimental data, our "instantaneous" curve and Draxler's "time-averaged" curve provide similar relationships with travel time, but as expected, the instantaneous factors are several times smaller than the time-averaged values. It should be noted that Equation (7) approaches zero for travel times on the order of 1500 s, so it would not be appropriate for receptors with source-to-receptor distances on the order of ≥1 km.

For near-source receptors, however, Equation (7) can be inserted into Equation (6) to estimate instantaneous diffusion coefficient as

$$\sigma_i = (\sigma_\theta \sigma_\phi)^{0.5} X [-0.1078 \ln(t) + 0.7898] \quad (8)$$

and minimal on-site input (i.e., X, U, σ_θ and σ_ϕ) are required for the calculation. Example results for the Galen data are given in Table 2. Note that the predicted values of σ_ι are within a factor of 2 of the observed values, and the average predicted-to-observed (P:O) ratio is 1.12.

Table 1. Galen 1997 Field Study - Test Conditions

Test	Date (D-M-YR)	Start Time(MDT)	X (m)	U (m s^{-1})	θ (deg)	σ_θ (deg)	σ_ϕ (deg)	Stability	T (K)	Q_{SF6} (g min^{-1})
S804c	04-08-97	1746	521	1.1	157	37	5	A	298	10.08
S804d	04-08-97	1906	521	1.9	163	56	7	A	296	10.01
S808c	08-08-97	1530	502	4.4	286	18	4	C	300	11.48
S808d	08-08-97	1638	478	4.0	303	19	5	C	298	11.41
S808e	08-08-97	1741	478	3.6	289	21	5	C	297	11.41
S808g	08-08-97	1924	520	4.1	360	11	4	D	293	11.27
S809b	09-08-97	1606	748	4.2	326	13	5	D	291	11.20
S8010c	10-08-97	1707	324	3.5	345	14	5	D	295	13.79

Test code – S: Galen fixed-point test
Test duration – 60 min
X – downwind distance
U – average wind speed
θ – average wind direction
σ_θ – standard deviation of horizontal wind fluctuations
σ_ϕ – standard deviation of vertical wind fluctuations
Stability – category based on the Sigma-A method (USEPA 1987).
T – ambient temperature
Q_{SF6} – release rate of tracer gas

Predicted values of σ_i are plotted against observed values of σ_i for the Galen 1997 experiments (Fig. 4). Also shown on the graph are results from applying the technique to field data from the Galen 1995/1996 study of Peterson et al. (1999), the Boardman tests of Peterson et at. (1999), the ERCB campaign of Peterson and Lamb (1995), and the Washington Desert Study of Peterson et al. (1990) and Peterson and Lamb (1992). This combined data set consists of 97 samples covering a range of terrain, meteorological conditions, and travel times. Overall, the method predicts observed values within a factor of 2, or better, for 94 percent of the cases, and within a factor of 3 for 100 percent of the experiments. In addition, the results are relatively unbiased with an average P:O ratio of 1.03 (with a standard deviation of 0.39).

In summary, we have developed and tested a simple way of predicting instantaneous plume spread for surface-level plumes from basic meteorological parameters. In the following section, we employ this technique in a meandering plume model to predict "real-time" concentration time series at fixed receptors.

The Meandering INstantaneous Diffusion (MIND) Model

While a diffusion coefficient is one component necessary to describe behavior of plumes in real time, another integral part is plume meander. To predict instantaneous concentrations downwind of a ground-level pollutant source, Peterson et al. (1990) and Peterson and Lamb (1992, 1995) developed a meandering plume model, and O'Neill (1996a, 1996b) packaged the approach into a program called the Meandering INstantaneous Diffusion (MIND) model. The core equation in MIND is

$$C_i = \frac{Q}{\pi \sigma_{yi} \sigma_{zi} u_i} e^{\frac{-(\theta_i - \theta_r)^2 (X\pi/180)^2}{2\sigma_{yi}^2}} \qquad (9)$$

where C_i is instantaneous concentration (mg m^{-3}) at a ground-level receptor; Q is contaminant release rate (mg s^{-1}); σ_{yi} and σ_{zi} are the instantaneous diffusion coefficients (m); u_i is wind speed near plume height (ms^{-1}); θ_i is a horizontal meander component (deg); θ_r is a bearing from the source to the receptor (deg); X is source-to-receptor distance (m); and (π/180) is a unit conversion to change degrees to meters.

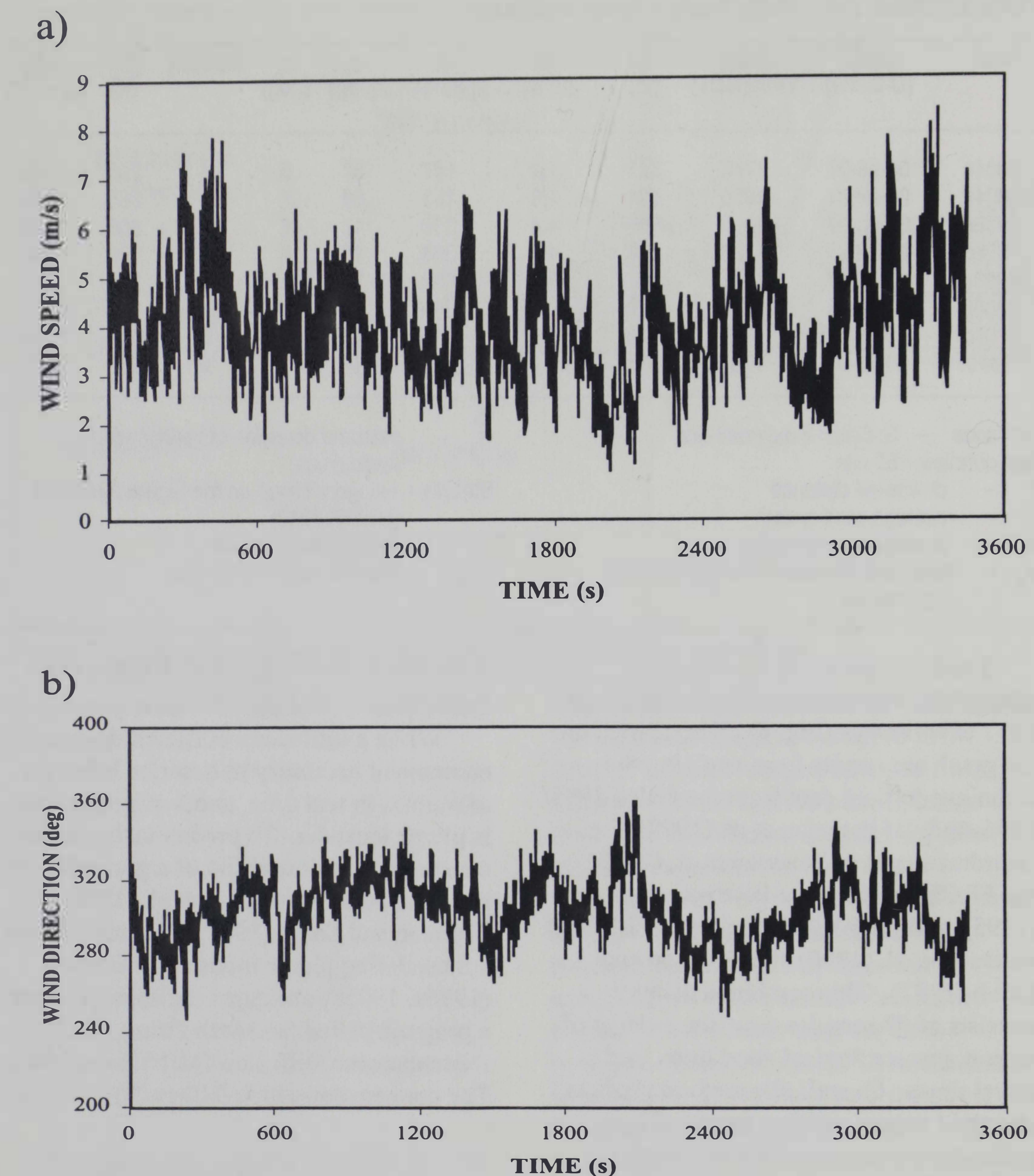

Figure 2. Time series of a) wind speed and b) wind direction for test S808d. Statistics include an average wind speed of 4 ms^{-1}, an average wind direction of 303°, and a standard deviation of wind azimuth of 19°.

The MIND model processes time series of uvw data from a propeller or sonic anemometer located near the source and near plume height. For each downwind distance, meander and wind speed components, θ_t and u_i, respectively, are resolved as running-average values using travel time for a smoothing time. Currently, several options are available in the model for instantaneous diffusion coefficients (σ_{yi} and σ_{zt}), including an option for user-specified entrees. Concentration time series are predicted for an array of receptors located downwind of the pollutant source. Corresponding concentration fluctuation statistics are calculated for each receptor, including mean concentration, intensity (ratio of concentration standard deviation to mean concentration), intermittency (fraction of time non-zero concentrations are

Table 2. Galen 1997 Study - Diffusion Data

Test	σ_ι (m)	t (s)	$(f_{1i}\,f_{2i})^{0.5}$	σ_ι^a (m)
S804c	23.9	453	0.200	15.6
S804d	15.7	282	0.090	31.7
S808c	17.0	115	0.216	21.9
S808d	19.7	119	0.241	22.4
S808e	16.2	133	0.185	23.0
S808g	18.8	127	0.281	17.9
S809b	31.5	179	0.284	25.6
S810c	20.0	94	0.429	14.0
Ratio P:O				1.12 (±0.45)

σ_ι – observed diffusion coefficient

t – travel time

$(f_{1i}\,f_{2i})^{0.5}$ – decay factor

σ_ι^a – predicted value from Equation(8) where $\sigma_\iota = (\sigma_\theta \sigma_\phi)^{0.5} \times [= -0.1078 \ln(t) + 0.7898]$

Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

recorded at a receptor), and peak-to mean ratio.

As an example, Figure 5a shows field data for Test S808d. These data were collected by the fast-response analyzer located 478 m downwind of the SF_6 source with a source-to-receptor bearing of 282°. Figure 5b illustrates the predicted concentration time series for that receptor using the MIND model with on-site uvw data and a value of 22.4 m for the diffusion component as calculated by Equation (8). Both time series contain comparable temporal features caused by meander and similar concentration values in response to spread of the instantaneous plume.

Figures 6a-6d contain the corresponding modeled crosswind profiles of mean concentration, intensity, intermittency factor, and peak-to-mean ratio in addition to the field data for Test S808d. The profiles agree with data collected in previous field campaigns (i.e., Hanna 1984, Lewellen and Sykes 1986, Peterson and Lamb 1995, and Sawford 1985). Specifically, crosswind mean concentration profiles were nearly Gaussian (Peterson and Lamb 1995); intensity values on the mean plume axis were near 1.0, and at the plume edges they were of order 10 (Hanna 1984, Lewellen and Sykes 1986, Peterson and Lamb 1995, and Sawford 1985); intermittency factors ranged from 0.5 to 0.8 near the plume axis and from 0.1 to 0.3 at crosswind positions near $2\sigma_y$ (Hanna 1984, Peterson and Lamb 1995, and Sawford 1985); and peak-to-mean ratios were near 2-10 at the centerline and near 30-100, and higher, at plume edges (Csanady 1967, Hanna 1984, Peterson and Lamb 1995, and Sawford 1985).

The concentration fluctuation statistics for all Galen 1997 field experiments are presented in Table 3 in addition to predictions from the MIND model. The one-hour test period was chosen because it corresponds to the smallest averaging period in the regulatory models, and the sampling rate of 1 Hz gives us near-instantaneous fluctuation data on the order of human breathing rates. The fluctuation statistics are depicted in terms of one-to-one correspondence between the field data and the model (Fig. 7). Time series variability is particularly well represented by the method as evident from the model performance for intensity, intermittency, and peak-to-mean ratios. Regarding time-averaged exposure, the model is conservative with an average predicted-to-observed ratio of 1.82.

In terms of limitations of the MIND model, concentration fluctuation statistics in this work represent 1-Hz data throughout sampling periods of approximately one hour; thus, model data and field data do not resolve fluctuations with higher frequencies. Again, the one-hour sampling period was chosen because it corresponds to the smallest averaging period in existing regulatory models. Regarding the sampling rate, a few field campaigns in the literature utilize faster sampling rates (i.e., up to 270 Hz by Yee et al. 1994), but high-frequency concentration fluctuations are filtered in the lungs, and 1-Hz data are believed to adequately represent near-instantaneous exposure associated with human breathing

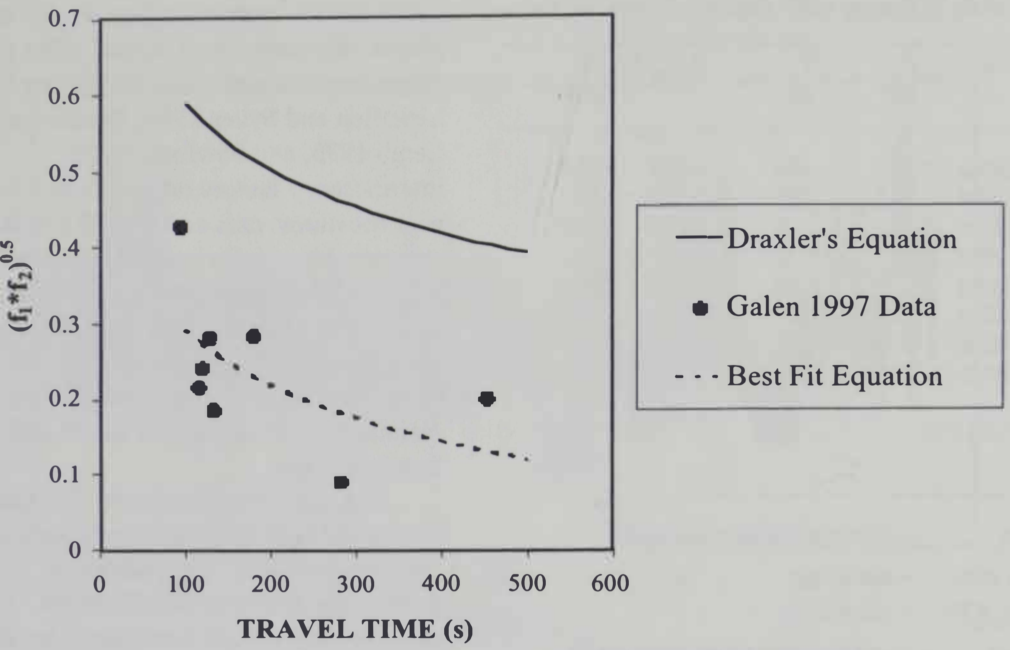

Figure 3. Instantaneous decay function versus travel time for the Galen 1997 data. A curve is shown representing a "best-fit" to the field data in addition to a "time-averaged" curve from Draxler (1976).

rates.

Other limitations involve source-to-receptor distance, plume profile, and wind speed. The MIND model has not been tested for receptors located farther than about 1 km from the source. Short-term plume behavior is most important for regulatory issues where the plume is narrow and concentrations are high, and other field campaigns will provide data for greater downwind distances in particular for stable conditions when instantaneous plume

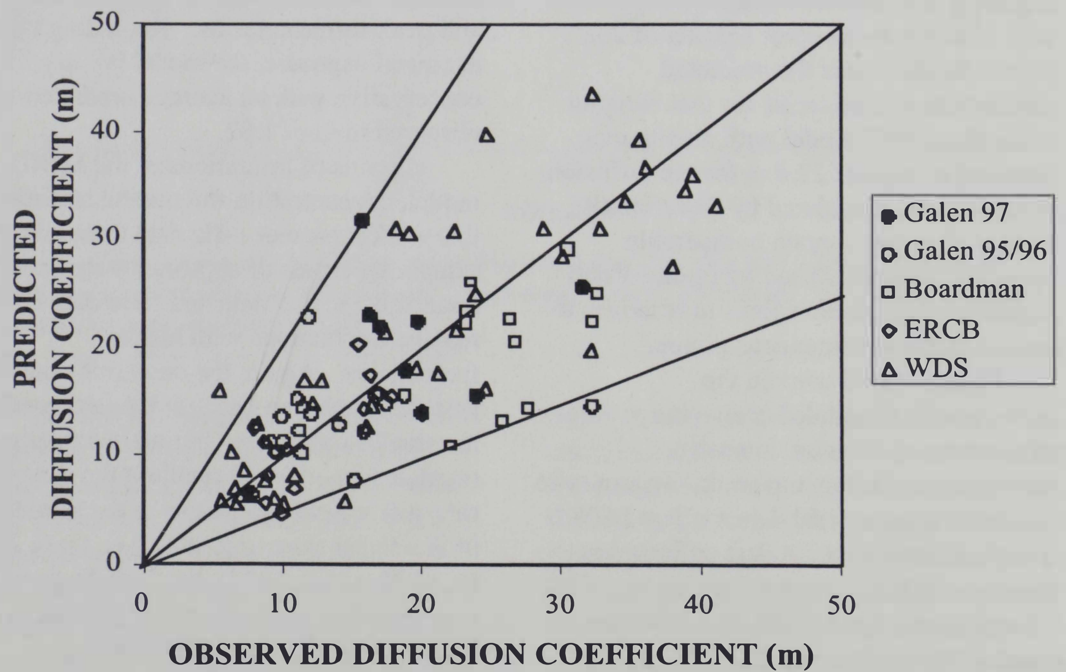

Figure 4. Predicted instantaneous diffusion coefficients versus observed values for five independent field campaigns.

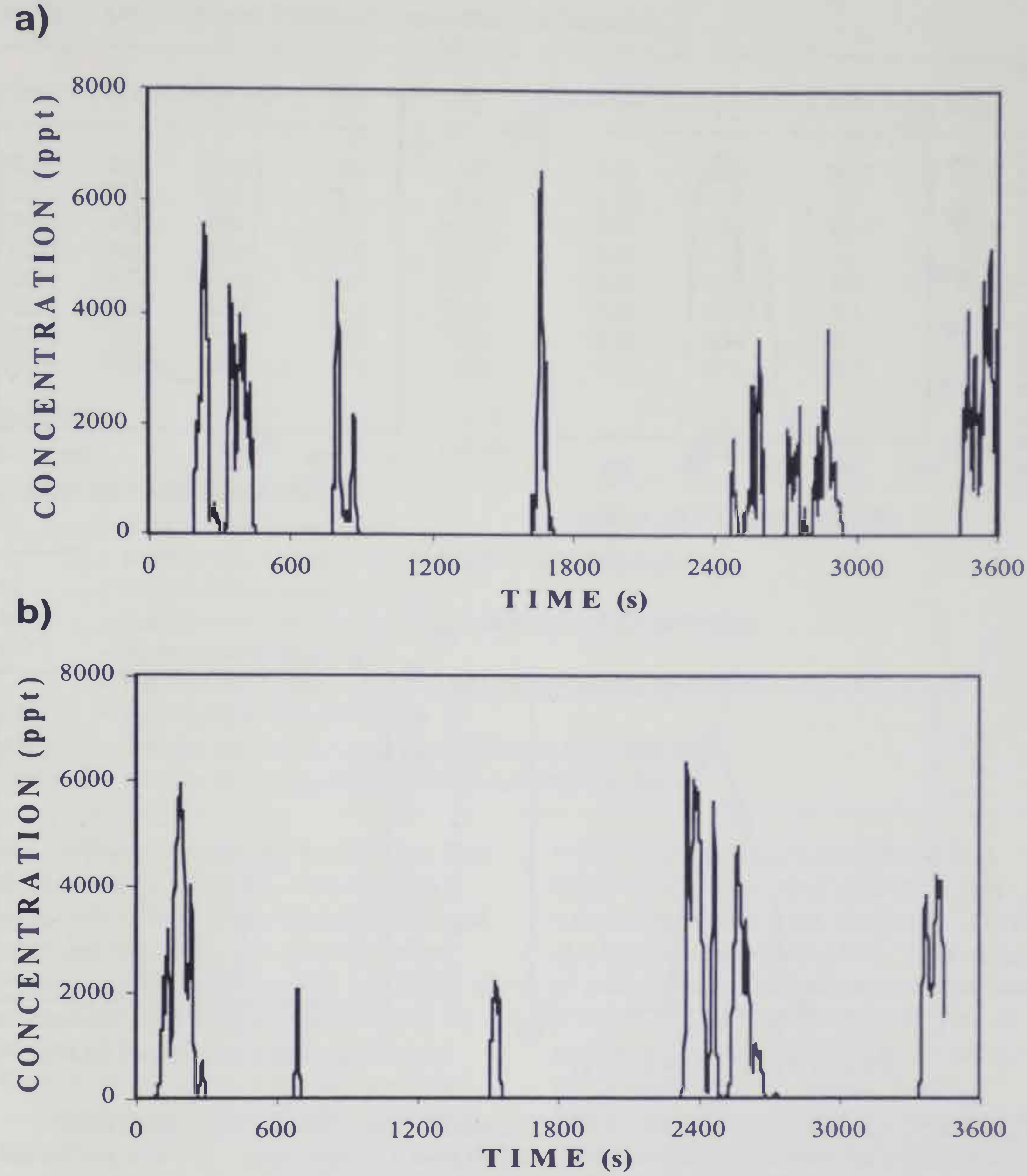

Figure 5. Concentration data for test S808d including a) time series of observations from the fast-response SF_6 analyzer at a receptor angle of 282°, b) predictions from the MIND model using Equation (8) for the diffusion coefficient. Also shown are 1:1, 1:2, and 2:1 lines-of-correspondence.

growth is slow and meander motions are large. In addition, vertical and horizontal profiles of the instantaneous plume are represented by smooth Gaussian functions; additional high-frequency fluctuations may result from patches of irregular internal plume structure. Finally, the largest uncertainties in the model correspond to conditions with weak winds. When wind speeds are less than about 1 ms^{-1}, variable wind directions may cause plume material to follow complicated paths between source and receptor. To date, few data have been collected under low-wind conditions to test and improve this aspect of the model, but in subsequent papers, we will address these uncertainties.

Normalized Peak Concentratrations

While the MIND model has been shown to reproduce field data under a range of meteorological conditions and amid a variety of roughness elements, the

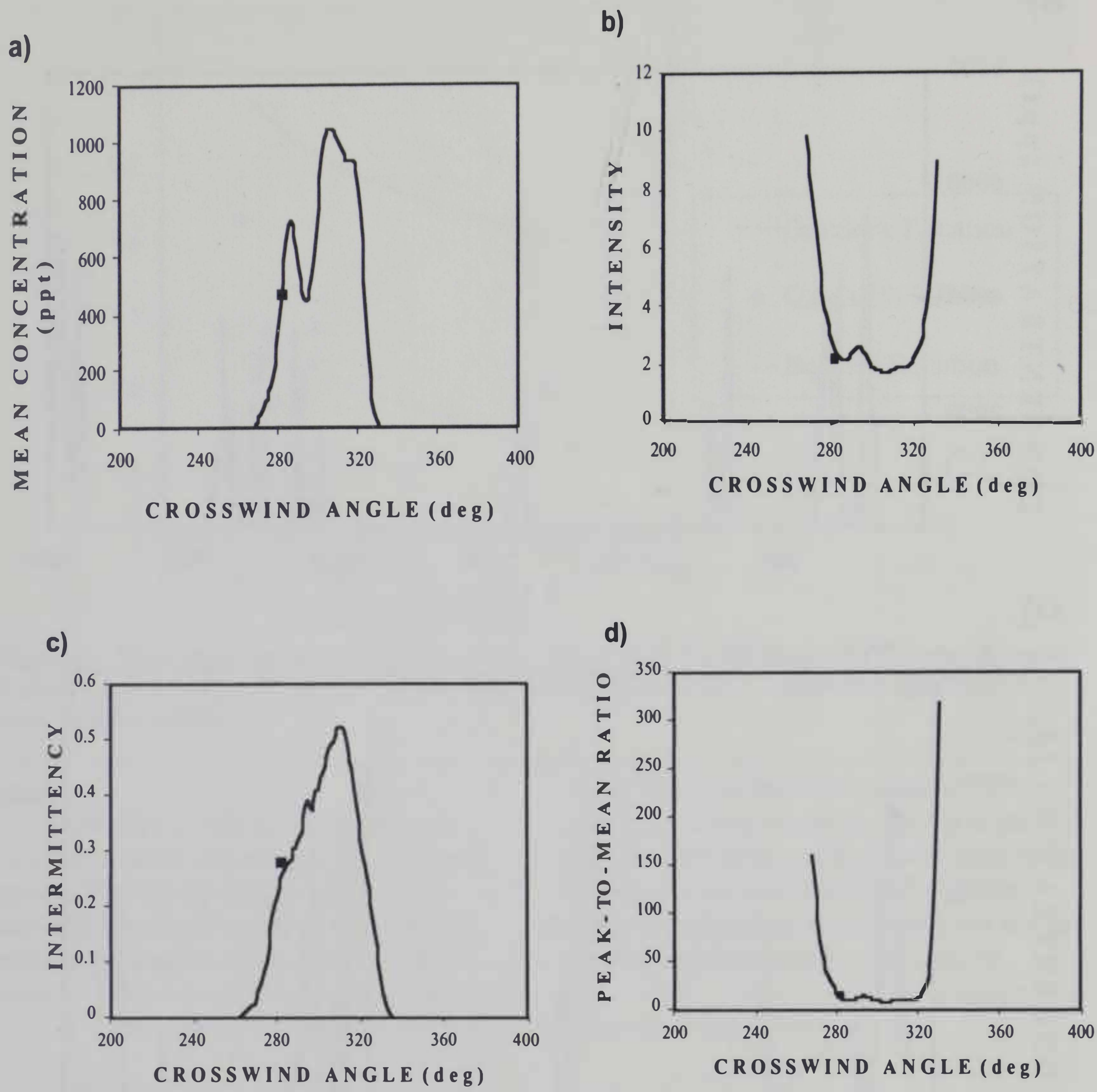

Figure 6. Crosswind profiles from the MIND model for test S808d, including a) mean concentration, b) intensity, c) intermittency, and d) peak-to-mean ratio. The statistic for the observed time series (shown in Figure 5a) is indicated by a "square".

"instantaneous" approach of predicting short-term exposure from real-time wind data is probably unrealistic for regulatory applications. The standard Gaussian model, however, could be used to predict a short-term peak concentration (C_p) for ground-level plumes as

$$C_p = \frac{Q}{\pi \sigma_{yi} \sigma_{zi} u} \qquad (10)$$

or in normalized form:

$$C_p \frac{u}{Q} = \frac{1}{\pi \sigma_{yi} \sigma_{zi}} \qquad (11)$$

where, again, Q is the mass release rate of pollutant; u is wind speed near source height; and instantaneous plume spread is determined by $\sigma_{yi}\sigma_{zi}$ or σ_i^2. For this work, normalized peak concentration in Equation (11) is assumed to represent a value with a time scale on the order of 1 sec if Equation (8) is used to estimate plume spread.

Table 4 contains normalized peak concentration ($C_p u/Q$) for the Galen 1997 experiments in addition to predictions from Equation (11) with Equation (8) for σ_i. For these data, the method produces an average P:O ratio of 1.19. Results are shown for

Table 3. Observed and Predicted Concentration Statistics

Test	C_o (ppt)	C_p ^{a} (ppt)	IN_o	IN_p ^{a}	I_o	I_p ^{a}	P/M_o	P/M_p ^{a}
S804c	530	1314	3.5	4.5	0.35	0.09	25.9	32.2
S804d	2622	1024	1.9	2.0	0.43	0.29	7.5	6.1
S808c	603	794	2.1	1.9	0.47	0.45	13.7	10.6
S808d	465	507	2.2	2.5	0.28	0.25	14.1	12.5
S808e	1477	1300	1.5	1.6	0.66	0.55	6.8	10.3
S808g	1361	1856	1.2	1.6	0.65	0.54	5.1	6.4
S809b	221	953	1.8	1.4	0.39	0.59	10.7	4.9
S810c	1025	2772	1.6	2.0	0.51	0.46	8.7	9.0
Ratio P:O		1.82 (±1.27)		1.10 (±0.19)		0.86 (±0.35)		1.00 (±0.33)

Test Duration = approximately 60 min

C_o – observed mean concentration
C_p ^{a} – predicted mean concentration from MIND using Equation(8) for σ_i
IN_o – observed concentration intensity
IN_p ^{a} – predicted concentration intensity from MIND using Equation(8) for σ_i
I_o – observed intermittency factor
I_p ^{a} – predicted intermittency factor from MIND using Equation(8) for σ_i
P/M_o – observed peak-to-mean ratio
P/M_p ^{a} – predicted peak-to-mean ratio from MIND using Equation(8) for σ_i
Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

the 1997 experiments and for the other four field campaigns (Fig. 8). The equation overpredicts in 60 percent of the cases, and underpredicts in 40 percent of the tests. Performance statistics include the effects of a few large outliers, but approximately 83 percent of the data are within a factor of three, or better, and the average predicted-to-observed ratio is 1.90 for the combined data set.

Similar to the limitations and uncertainties of the MIND model, this method of predicting normalized peak concentrations has not been tested for downwind distances greater than 1 km. Non-Gaussian plume profiles induce uncertainty to the results, and additional field data are required for stable meteorological conditions with low wind speeds. For the range of conditions tested, however, the simple approach is expected to provide realistic, yet conservative, estimates of peak concentration.

Summary

In this paper, we presented results from recent field studies regarding short-term behavior of surface-level plumes. Eight tracer experiments were conducted in 1997 at a field site near Galen, MT. Time series of concentration fluctuations were collected at a rate of 1 Hz with fast-response tracer analyzers operating 324-748 m downwind of a ground-level SF_6 source. Wind conditions were monitored near the surface throughout the campaign, and stability categories ranged from neutral through extremely unstable.

Using the Galen field data, we developed a simple approach to estimate instantaneous spread for surface-level plumes. The approach was similar to the work by Draxler (1976) except an instantaneous time frame is represented instead of a time-averaged time frame. An empirical function was derived for s_i as a function of travel time, and the equation performed within a factor of 2, or better, for 94 percent of a dataset consisting of 97 samples covering a range of terrain types, meteorological conditions, and travel times. Furthermore, the results were nearly

Table 4. Normalized Peak Concentrations

Test	$C_pu/Q \times 10^6(m^{-2})$	$C_pu/Q^a \times 10^6(m^{-2})$
S804c	479	1314
S804d	1119	316
S808c	941	662
S808d	694	631
S808e	954	604
S808g	771	998
S809b	275	486
S8010c	681	1625
Ratio P:O		1.19(±0.84)

C_pu/Q – observed normalized peak concentration
C_pu/Q^a – predicted value from $(p\,\sigma_i^2)^{-1}$ using Equation (8) for σ_i
Ratio P:O – average ratio of predicted-to-observed (± standard deviation)

unbiased with an average predicted-to-observed (P:O) ratio of 1.03.

The field data were also used to test the Meandering INstantaneous Diffusion (MIND) model. We processed wind data into separate meander and diffusion components and predicted concentration time series for receptors corresponding to the location of the tracer analyzer in each experiment. The model predicted concentration patterns that were quite similar to the field data. In terms of concentration fluctuation statistics, the MIND model produced average predicted-to-observed ratios close to one for intensity, intermittency, and peak-to-mean ratio. The average P:O ratio for mean concentration was 1.82.

Finally, we proposed a simple approach to predict short-term peak concentrations. We modeled normalized peak concentration (C_pu/Q) for a ground-level source as $(\pi\sigma_{yi}\sigma_{zi})^{-1}$ or $(\pi\sigma_i^2)^{-1}$ with Equation (8) for σ_i. Values for the 1997 Galen experiments were combined with field data from Peterson et al. (1999), Peterson and Lamb (1995), Peterson et al. (1990) and Peterson and Lamb (1992). Overall, normalized peak concentrations were predicted within a factor of 3, or better, for 83 percent of the observed values, and the average P:O ratio was 1.90. Additional meteorological and terrain conditions should be tested, but this type of approach would be elementary to incorporate into a Gaussian-based

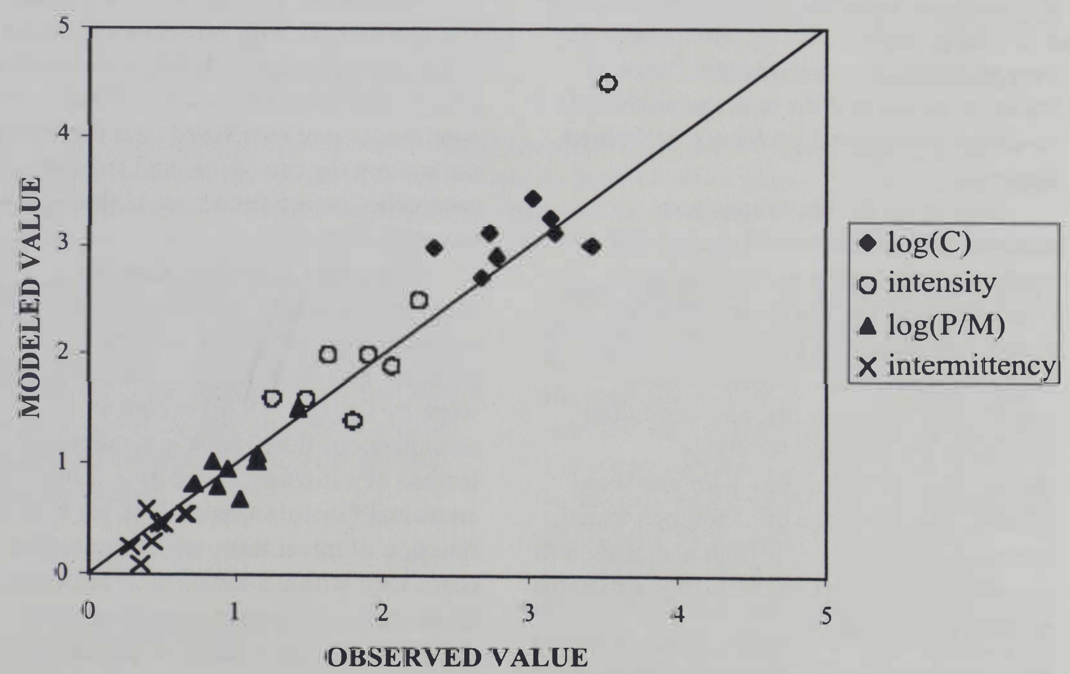

Figure 7. Predicted concentration fluctuation statistics from the MIND model versus observed values for the Galen 1997 experiments. Also shown is the 1:1 line-of-correspondence.

regulatory model such as ISC or SCREEN, and the end product would be hourly predictions of instantaneous peak concentration in addition to existing estimates of mean concentration.

Acknowledgements

This material is based upon work supported by the U. S. Army Research Office under contract/grant numbers DAAH04-94-G-0349 and DAAG55-98-0241. The authors specifically thank Dr. Walter Bach. Dione Mazzolini and Charles Mazzone are appreciated for assistance in fieldwork. Finally, landowners at the Galen site (Mr. Hans Lampert, Mr. Donald Beck, Dr. Elaine Stasney, and Dr. Mike Murnick) are also acknowledged.

Literature Cited

Benner, R. L., and B. Lamb. 1985. A fast response continuous analyzer for halogenated atmospheric tracers. Journal of Atmospheric and Oceanic Technology. 2:582-589.

Csanady, G. T. 1967. Concentration fluctuations in turbulent diffusion. Journal of Atmospheric Sciences. 24:21-28.

Dinar, N., H. Kaplan, and M. Kleiman. 1988. Characterization of concentration fluctuations of a surface plume in a neutral boundary layer. Boundary-Layer Meteorology. 45:157-175.

Donovan, T. 1998. A comparison of observed concentration fluctuations to predictions from a meandering plume model. M.S. thesis. Montana Tech of the University of Montana, Butte. 117 pp.

Draxler, R. R. 1976. Determination of atmospheric diffusion parameters. Atmospheric Environment. 10:99-105.

Jones, C. D. 1983. On the structure of instantaneous plumes in the atmosphere. Journal of Hazardous Materials. 7:87-112.

Jørgensen, H. E., and T. Mikkelsen. 1993. Lidar measurements of plume statistics. Boundary-Layer Meteorology. 62:361-378.

Joshi, N. 1998. An investigation of instantaneous plume spread under neutral through extremely stable conditions. M.S. thesis. Montana Tech of the University of Montana. Butte. 122 pp.

Hanna, S. R. 1984. Concentration fluctuations in a smoke plume. Atmospheric Environment. 12: 1091-1106.

Gifford, F. A. 1959. Statistical properties of a fluctuating plume dispersion model. Advances in Geophysics, Volume 6, Academic Press, 117-137.

Lewellen, W. S., and R. I. Sykes. 1986. Analysis of concentration fluctuations from lidar observations of atmospheric plumes. Journal of Climate and Applied Meteorology. 25:1145-1154.

Mylne, K. R. 1992. Concentration fluctuation measurements in a plume dispersing in a stable surface layer. Boundary-Layer Meteorology. 60:15-48.

_____, and P. J. Mason. 1991. Concentration fluctuation measurements in a dispersing plume at a range up to 1000 m. Quarterly Journal of the Royal Meteorological Society. 30:177-206.

O'Neill, S. 1996a. The Meandering INstantaneous Diffusion (MIND) Model. M.S. thesis. Montana Tech of the University of Montana. Butte. 76 pp.

_____. 1996b. Development and testing of a model for instantaneous plume dispersion. Pp. 364-357 in Preprint Volume of Ninth Joint Conf. on the Applications of Air Pollution Meteorology with A&WMA, 28 January – 2 February 1996. Atlanta GA by the AMS, Boston, MA.

Peterson, H. G., D. Mazzolini, S. M. O'Neill, and B. K. Lamb. 1999.

Instantaneous spread of plumes in the surface layer. Journal of Applied Meteorology. 38:343-352.

_____, and B. K. Lamb. 1995. An investigation of instantaneous diffusion and concentration fluctuations. Journal of Applied Meteorology. 34:2724-2746.

_____, and _____. 1992. Comparison of results from a meandering-plume model with measured atmospheric tracer concentration fluctuations. Journal of Applied Meteorology. 31:553-564.

_____, _____, and D. Stock. 1990. Interpretation of measured tracer concentration fluctuations using a sinusoidal meandering plume model. Journal of Applied Meteorology. 29:1284-1299.

Sawford, B.L. 1985. Atmospheric boundary-layer measurements of concentration statistics from isolated and multiple sources. Boundary-Layer Meteorology. 31:249-268.

U.S. Environmental Protection Agency. 1987. On-site meteorological program guidance for regulatory modeling applications. EPA-450/4-87-013. Office of Air Quality Planning and Standards. Research Triangle Park, NC, 172 pp.

Yee, E., P. R. Kosteniuk, G. M. Chandler, C. A. Biltoft, and J. F. Bowers. 1993. Statistical characteristics of concentration fluctuations in dispersing plumes in the atmospheric surface layer. Boundary-Layer Meteorology. 65:69-109.

_____, R. Chan, P. R. Kosteniuk, G. M. Chandler, C. A. Biltoft, and J. F. Bowers. 1994. Experimental measurements of concentration fluctuations and scales in a dispersing plume in the atmospheric surface layer obtained using a very fast response concentration detector. Journal of Applied Meteorology. 33:996-1016.

Received 19 July 2003
Accepted 11 December 2003