A RE-EXAMINATION OF PARTICULATE DISPERSION MODELING FOR COTTON GINS

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Abstract

This paper will examine the use of the Industrial Source Complex (ISC) model for air dispersion modeling of particulate matter. The ISC model is currently the most popular dispersion model approved for use by the Environmental Protection Agency (EPA). A new dispersion model, the Fritz-Zwicke Model ©, has been developed by the authors to more accurately predict the ambient concentration downwind from a pollutant emission source. Both models are based upon the Gaussian diffusion equations; however, the parameters of the Gaussian model are applied differently in each. The ultimate goal of this project is to have the Fritz-Zwicke Model © approved by EPA Region VI for future use in the regulation of air pollution from agricultural operations, including cotton gins.

Introduction

Dispersion modeling is quickly becoming an increasingly more important part of the air pollution regulatory process. The use of air dispersion modeling can allow a modeler to predict the contribution of pollutant to the ambient concentration downwind from an emission source, including an agricultural source, such as a cotton gin. The accuracy of this prediction depends upon the accuracy of the dispersion model being used. Since air dispersion modeling has become such a significant part of the regulatory process, it is essential to use an accurate model.

The Gaussian dispersion model is the most popular basis for determining the impact of nonreactive pollutants, such as particulate matter. (EPA, 1986) This model may be used to estimate the ground-level concentrations downwind in a plume from a source with a specific emission rate. (Gifford, 1975) A coordinate system is incorporated where the origin is placed at the base of the stack with the x-axis aligned in the downwind direction. "The contaminated air stream (normally called a plume) rises from the stack and then levels off to travel in the x-direction and spread in the y- and z-directions as it travels. For Gaussian plume calculations, the plume is assumed to be emitted from a point with coordinates (0,0,H), where H refers to the effective stack heigh, which is the sum of the physical stack height (h) and the plume rise (Δh)." (DeNevers, 1995) The Gaussian dispersion equation for determining ground-level concentrations is shown in equation (1):

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_z^2}\right)\left[\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right] \qquad (1)$$

where: C 0 steady-state concentration ($\mu g/m^3$),
Q = emission rate ($\mu g/s$),
π = 3.14159...,
u = wind speed at stack height (m/s),
σ_y = lateral dispersion parameter (m),
σ_z = vertical dispersion parameter (m),
z = receptor height (m), and
H = plume centerline height (m).

The following assumptions are associated with the use of the Gaussian model (Turner, 1994):

- The emission rate of pollutant does not vary over time.
- No pollutant is lost due to chemical reaction, settling, or turbulent impaction during transport.
- Meteorological conditions remain constant over the time of transport.
- The crosswind and vertical concentration distributions are well-represented by a Gaussian, or normal, distribution at any distance downwind or any distance in the crosswind directions.

Veigele and Head (1978) noted, "The assumptions used in the derivation, frequently, do not hold. Emissions may vary with time. Pollutants may be lost due to settling or chemical reactions. Wind fields may vary with height. Inversion layers may exist. The diffusion constants may vary. Because of these and other cases where the assumptions do not hold, care must be taken when using the Gaussian equation." In order to produce concentration estimates that are as accurate as possible, the Gaussian dispersion model should be applied to a situation that satisfies as many of these assumptions as possible. (Fritz, et al., 1997)

The dispersion parameters, σ_y and σ_z, were developed by Pasquill (1961), who observed plumes of sulfur dioxide (SO_2) and smoke (gases and particulate matter) over two- to three-minute time intervals. Figure 1 (Turner, 1994) illustrates the function of the dispersion parameters in the double normal distribution of concentration estimates.

The most common model approved for use by EPA is the ISC model, which is based on Gaussian diffusion. The ISC model has three main components:

- SCREEN--a simple screening algorithm used to determine a one-hour average concentration,

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- ST--uses weather data recorded in one-hour intervals to determine shorter-term (up to one year) average concentrations, and
- LT--used to determine longer-term (greater than one year) average concentrations.

The National Ambient Air Quality Standards (NAAQS) for particulate matter are based on 24-hour and one year average concentrations. Therefore, only SCREEN and ST will be evaluated for the purposes of this research.

The time average concentration is greatly influenced by the variation in wind speed and direction over the time period. For example, given a particular sampling location in a downwind direction over a two-minute time period, there is a good chance that wind speed and direction will remain constant. This will result in a relatively high two-minute average concentration at that sampling location. For a 24-hour time period at the same sampling location, however, there may be a great variation in wind speed and direction. This will cause the 24-hour concentration to be lower than the two-minute concentration, since there will periods in the averaging time when no particulate is being sampled, due to the flow of wind in a direction away from the sampler. In general, "a longer time-averaged concentration would be expected to be less than a short time-average, owing to wind shifts and turbulent diffusion." (Cooper and Alley, 1994)

Discussion

The use of SCREEN and ST results in an inaccurate prediction of downwind concentrations. Both SCREEN and ST are used to predict a one-hour concentration from a direct application of the Gaussian model. This application involves the assumption that wind speed and direction remain completely constant over a one-hour period. Pasquill (1961) stated that, "...it is difficult, if not impossible to find any example of atmospheric turbulence in which the conditions are strictly satisfied." The conditions to which Pasquill was referring to were the conditions of constant wind speed and direction. Williams (1996), in her research, concluded: "The current method of using ISC SCREEN results in inaccurate (excessively high) predictions of downwind concentrations. Any method used to model air quality should be conservative in nature. However, an extremely conservative prediction of property line concentrations used as a permitting tool could result in unjustified, mandated controls on an industry. Therefore, it is essential that a new model be developed for the purpose of accurately predicting downwind concentrations when compared to ISC SCREEN."

When predicting downwind concentrations with SCREEN, many regulators use only the full-meteorology option. The use of this option allows the modeler to find the combination of atmospheric stability class and wind speed at which the highest downwind concentration is predicted. The modeler adds an excessive degree of conservatism to the predicted concentrations when using this option, as will be shown in the results section of this paper. The use of ST requires the input of weather data recorded at one-hour intervals. This data is usually taken at one instant in time during the one-hour time period, and, therefore, may not be representative of the actual wind speed and direction during that period. This data definitely does not accurately represent the variation in wind speed and direction that may take place during the one-hour period.

In order to more accurately predict the ambient concentration of pollutant downwind from an emission source, the authors of this paper have developed a new dispersion model--the Fritz-Zwicke Model ©. This model is based on the Gaussian dispersion equation and requires the input of weather data in two-minute intervals to predict downwind concentrations, which is the same time interval used to develop the dispersion parameters of the Gaussian equation.

It was desired by the authors to perform ambient sampling of concentrations downwind from a stack and to compare the concentrations measured from sampling with predicted concentrations obtained from the use of SCREEN, ST, and the Fritz-Zwicke Model ©. A site was chosen at the Riverside campus of Texas A&M University on an unused airport runway. A stack was constructed to supply a constant emission rate of particulate with a known particle size distribution. The particulate used was fly ash, of which approximately 65% consisted of particles less than or equal to ten microns in aerodynamic equivalent diameter (PM_{10}). EPA reference method PM_{10} samplers were also located in various positions downwind from the source to measure the concentration of PM_{10} at those locations. A weather station was placed at the site to record the wind speed and direction at two-minute intervals. Each test was conducted for approximately a one-hour period, which correlates to the time-averaged concentration predicted by the use of SCREEN and ST.

During the modeling portion of the tests, SCREEN was used with the full-meteorology option used by many regulators, as well as with the average atmospheric stability class and wind speed for the test period. Each of the recorded weather data points during the tests were eligible to be entered as the one-hour data into ST, and, therefore, a range of predicted concentrations, as well as the standard deviation of the range of concentrations were reported. ST was also used with the average wind speed and direction obtained during the tests. The Fritz-Zwicke Model © was used directly with the recorded two-minute weather data recorded during the tests.

Results

Test 1

Test 1 was conducted over a 60-minute period. For this test, samplers 1, 2, and 3 were placed 200, 300, and 400 meters, respectively, due north of the stack. Samplers 4, 5, and 6 were placed 200, 300, and 400 meters, respectively, away from the stack at 50 degrees west of north. Figure 2 represents the windrose obtained from the recorded weather data for the first test. As can be seen from Figure 2, there was a fairly large variation in wind direction over this 60-minute period.

Table 1 represents the results of Test 1. At sampler 1, the measured concentration was 35 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 73 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 244 µg/m^3, with a standard deviation of 90 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 236 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 2029 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 733 µg/m^3.

At sampler 2, the measured concentration was 29 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 32 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 123 µg/m^3, with a standard deviation of 41 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 102 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1861 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 390 µg/m^3.

At sampler 3, the measured concentration was 18 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 17 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 73 µg/m^3, with a standard deviation of 23 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 53 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1880 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 240 µg/m^3.

At sampler 4, the measured concentration was 55 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 62 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 741 µg/m^3, with a standard deviation of 170 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 0 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 2029 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 733 µg/m^3.

At sampler 5, the measured concentration was 32 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 27 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 329 µg/m^3, with a standard deviation of 75 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 0 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1861 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 390 µg/m^3.

At sampler 6, the measured concentration was 24 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 14 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 175 µg/m^3, with a standard deviation of 39 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 0 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1880 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 240 µg/m^3.

The predicted concentrations obtained from the use of the Fritz-Zwicke Model © most closely resembles the actual measured concentrations from the first test. The use of ST resulted in a high variability of predicted values, and the use of SCREEN excessively over-predicted the concentrations.

Test 2

Test 2 was conducted over a 56-minute period. Samplers 1, 2, 3, and 4 were located at 200, 300, 400, and 500 meters, respectively, due north of the stack. Figure 3 represents the windrose obtained from the recorded weather data for the second test. There was not much variation in wind direction for test 2.

Table 2 represents the results of Test 2. At sampler 1, the measured concentration was 24 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 60 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 232 µg/m^3, with a standard deviation of 78 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 32 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 2018 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 231 µg/m^3.

At sampler 2, the measured concentration was 30 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 40 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 161 µg/m^3, with a standard deviation of 54 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 19 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1877 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 143 µg/m^3.

At sampler 3, the measured concentration was 27 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 27 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 112 µg/m^3, with a standard deviation of 37 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 12 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1861 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 95 µg/m^3.

At sampler 4, the measured concentration was 17 µg/m^3. The use of the Fritz-Zwicke Model © resulted in a predicted concentration of 20 µg/m^3. The use of ST with each weather data point resulted in a predicted concentration that ranged from 0 to 82 µg/m^3, with a standard deviation of 27 µg/m^3. The use of ST with the average wind speed and direction for the test period produced a concentration of 8 µg/m^3. The use of SCREEN with the full-meteorology option resulted in a predicted concentration of 1738 µg/m^3, while the use of SCREEN with the average atmospheric stability class and wind speed produced a concentration of 68 µg/m^3.

Again in Test 2 as in Test 1, the predicted concentrations obtained from the use of the Fritz-Zwicke Model © most closely resemble the actual measured concentrations. The use of ST resulted in a high variability of predicted values, and the use of SCREEN excessively over-predicted the concentrations.

Summary

The EPA-approved ISC models are inaccurate. This inaccuracy could result in a cotton gin or other source to be deemed out of compliance with the NAAQS by a regulatory agency, causing possible economic hardship for the operators of the source as they struggle to correct a perceived problem, which, in reality, is not a problem at all. The use of the Fritz-Zwicke Model ©, on the other hand, incorporates an application of the Gaussian model with two-minute weather data to provide a more accurate prediction of downwind concentration of pollutant. Accuracy is highly important in the dispersion modeling process, and there is an accurate model now available.

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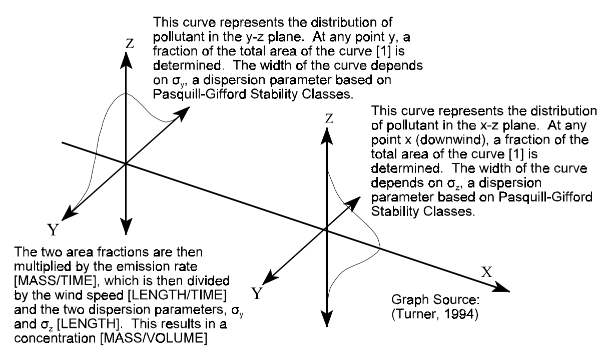

Figure 1.

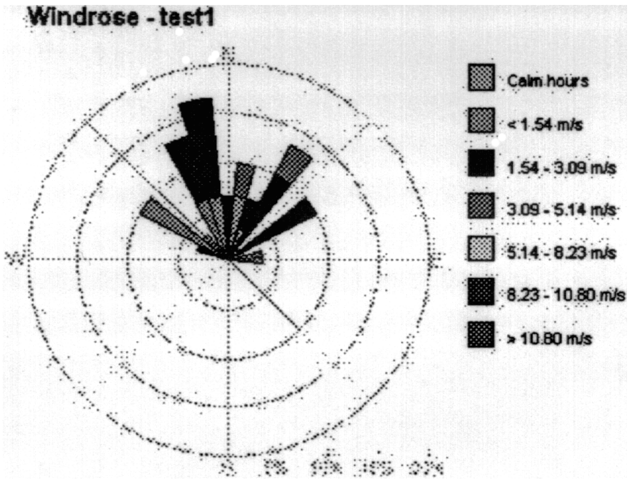

Figure 2.

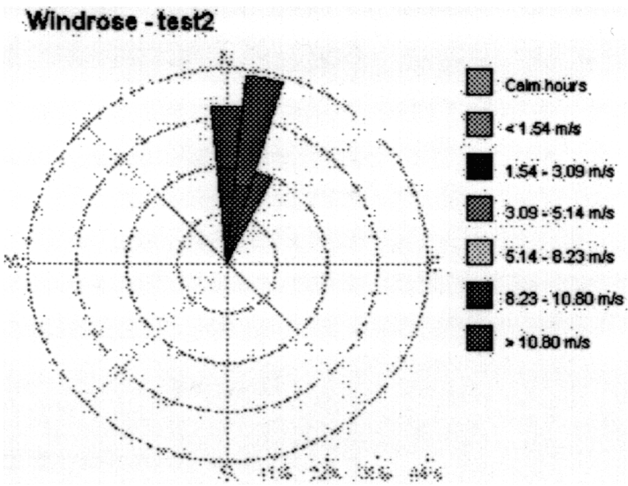

Figure 3.

Table 1.

	Sampler Number					
Concentration (μg/m^3)	**1**	**2**	**3**	**4**	**5**	**6**
Measured	35.35	28.93	18.03	55.12	32.36	23.63
Fritz-Zwicke ©	72.87	32.40	17.44	61.63	26.73	13.98
Low ST	0.00	0.00	0.00	0.00	0.00	0.00
High ST	244.40	123.10	72.63	741.15	329.20	174.75
ST Standard Deviation	90.24	41.23	22.85	169.78	74.66	39.35
ST (Avg. Wind)	235.88	101.70	53.31	0.00	0.00	0.00
SCREEN (Full Meteorology)	2029.0	1861.0	1880.0	2029.0	1861.0	1880.0
SCREEN (Avg. Wind)	732.70	390.10	240.20	732.70	390.10	240.20

Table 2:

	Sampler Number			
Concentration (μg/m^3)	**1**	**2**	**3**	**4**
Measured	23.79	30.41	26.52	17.01
Fritz-Zwicke ©	60.30	40.32	27.48	19.78
Low ST	0.00	0.00	0.00	0.00
High ST	232.47	160.82	112.20	82.21
ST Standard Deviation	77.69	53.72	37.48	27.48
ST (Avg. Wind)	31.70	18.85	11.71	7.80
SCREEN (Full Meteorology)	2018.00	1877.00	1861.00	1738.00
SCREEN (Avg. Wind)	231.00	143.00	95.08	67.69