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Dispersion Modeling of Agricultural Low Level Point Sources

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Abstract. *Cotton gins, feed mills, and grain elevators are examples of low level point sources that are permitted based upon the predicted concentrations from dispersion modeling. ISCST3, the current EPA approved dispersion model for low level point sources, uses an emission rate developed from the emission factors listed in AP42 to predict a 10-minute downwind concentration. This paper addresses the problems associated with the errors in the emission factors listed in AP42 as well as those associated with the assumption by the developers of ISCST3 that a 10-minute concentration is equal to a 60-minute concentration.*

The six Pasquill-Gifford stability classes, used by ISCST3, were developed from 10-minute average field data and can only be used to calculate 10-minute concentrations. In addition, the meteorological data (wind speed and direction) used in ISCST3 is a 10-minute average that is assumed to be a 60-minute average. These assumptions cause ISCST3 to over-predict downwind concentrations by approximately 2.5 times. Monte Carlo simulations and the power law model were used to develop P values (dependent upon stability class and down wind distance) that were used to give a more accurate prediction of downwind concentrations.

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The emission factors used in AP42 were modified based upon a more accurate particle size distributions and more accurate cyclone efficiencies. These modified emission factors were used in an ISCST3 model. In each case, the modified emission factors reduced the predicted concentrations.

Keywords. Air Pollution, Dispersion Modeling, Emission Factor, Gaussian Dispersion, Power Law, Particulate Matter, Cotton Ginning

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Introduction

The operation of low level point sources such as cotton gins, grain elevators, and feed mills is dependent upon obtaining an air permit from the state air pollution regulatory agency (SAPRA). The SAPRA permitting process uses either direct field sampling data taken from the facility or dispersion modeling results to determine whether the facility is in compliance with the national ambient air quality standard (NAAQS). The NAAQS mandates that the 24 hour average property line concentration of PM_{10} be no greater than 150μg/m^3. PM_{10} is defined as particulate matter (PM) that has an aerodynamic equivalent diameter of 10μm or less.

The current dispersion model approved by the US EPA for modeling low level point sources is the Industrial Source Complex Short Term version 3 (ISCST3). ISCST3 is a Gaussian dispersion model that uses the Pasquill-Gifford horizontal and vertical plume spread parameters, σ_y and σ_z respectively. The calculation of σ_y and σ_z is dependent upon the Pasquill-Gifford atmospheric stability class and downwind distance (x). These dispersion parameters are used in the Gaussian dispersion equation along with emission rate, wind velocity, and effective emission height to calculate downwind concentrations. The concentrations predicted by the Gaussian model are 10 minute average concentrations (Cooper and Alley, 1994). This is due to the fact that the Pasquill-Gifford stability classes were developed from 10 minute average data. ISCST3 calculates 24 - 10 minute average concentrations (not 24 – 60 minute averages) and takes their average to be a 24 hour average. The error associated with this method is that wind direction changes within the hour are not taken into account. By not taking these fluctuations into consideration, the modeled concentrations are significantly over predicted.

Stiggins et al. (2002) developed a method by which the over prediction of downwind concentrations by ISCST3 can be corrected for. This approach utilizes Monte Carlo simulation (Crystal Ball, 2002) and the published wind standard deviations by the EPA (2000) to determine a set of P values to be used in the Hino power law model (Cooper and Alley, 1994) to convert 10 minute concentrations (C_{10}) to 60 minute concentrations (C_{60}). Hino (1968) states that for averaging periods between 10 minutes and 5 hours, a P value of 0.5 is appropriate. The list of P values determined by the Stiggins method lists an individual P value for each of the six Pasquill-Gifford stability classes (Cooper and Alley, 1994) not taking into account the downwind distance (x).

This research uses a modified version of the Stiggins method to demonstrate the over prediction errors associated with ISCST3. Regression equations to determine a P value dependent upon stability class and down wind distance (x) were developed using simulation (Crystal Ball, 2002). These P values were then used with the meteorological data published by Fritz (2002) and the Gaussian model to develop a more accurate estimate of 60 minute average concentrations.

The errors associated with the science that ISCST3 is based upon are confounded when the emission rates used in the modeling process are flawed. This problem is seen by cotton gins in a two fold manner. The emission factors published by EPA in 1996 AP-42 state that the PM_{10} percentage of TSP is 39%. This figure corresponds to an average mass median diameter (MMD) of 12.6 with geometric standard deviation (GSD) of 2.0. Buser (2002) suggests that a more accurate estimate of the average MMD and GSD of cotton gin dust is 18μm and 2.2, respectively.

Some SAPRAs estimate the collection efficiency of all cyclones on cotton gin exhausts to be 90%. Wang (2000) reported collection efficiencies for 1D2D and 1D3D cyclones to be in excess of 98%. The effect of this difference is seen in the mass of PM that penetrates the cyclone. A collection efficiency of 90% corresponds to a 10% penetration where a 98% collection efficiency corresponds to a 2% penetration. This in effect suggests that the emission factors from cotton gin cyclones could be over estimated by as much as 5 times.

These two scenarios were taken into account and ISCST3 models were developed to show the effect of assuming a new particle size distribution and new abatement system efficiencies. The models taking into account the errors in the emission factors from AP-42 indicate a significant difference in the predicted concentrations.

Methods

The Gaussian Dispersion Model

The Gaussian dispersion equation is used by ISCST3 to calculate 10 minute concentrations based upon the Pasquill-Gifford dispersion parameters σ_y and σ_z. To demonstrate this fact, a spreadsheet model was developed using the following equations to calculate values for the variables used in the Gaussian equation (equation 5). The calculation of σ_y and σ_z is accomplished using equations 1 and 2 respectively (Turner, 1994).

$$\sigma_y = \frac{1000 * X * \tan(T)}{2.15} \qquad (1)$$

$$\sigma_z = a * X^b \qquad (2)$$

Where

- σ_y, σ_z = Pasquill-Gifford horizontal and vertical dispersion parameters (m),
- X = distance down the centerline of the plume, see equation 3 (km),
- T = one half of Pasquill's θ, dependent upon stability class (see Table 1) (degrees),
- a, b = constants dependent upon stability class and X (see Table 2).

Table 1. Equations used to calculate T for use in the calculation of σ_y. Equations obtained from Turner (1994).

Stability Class	Equation for T
A (1)	$T = 24.167 - 2.5334 * \ln(X)$
B (2)	$T = 18.333 - 1.8096 * \ln(X)$
C (3)	$T = 12.5 - 1.0857 * \ln(X)$
D (4)	$T = 8.3333 - 0.72382 * \ln(X)$
E (5)	$T = 6.25 - 0.54287 * \ln(X)$
F (6)	$T = 4.1667 - 0.36191 * \ln(X)$

$$X = \frac{(x_{rec} - x_{source}) * \sin(\Theta) + (y_{rec} - y_{source}) * \cos(\Theta)}{1000} \qquad (3)$$

$$Y = (x_{rec} - x_{source}) * \cos(\Theta) - (y_{rec} - y_{source}) * \sin(\Theta) \qquad (4)$$

Where

- Y = horizontal distance from plume centerline (m),
- x_{rec}, y_{rec} = Cartesian coordinate location of the receptor measuring the C_{10} value (m),
- x_{source}, y_{source} = Cartesian coordinate location of the source (m)
- **Q** = wind direction (degrees) North corresponds to 0 or 365 and increases in a clockwise rotation.

Table 2. Values for the constants a and b used in the calculation of σ_z. Abridged table of values obtained from Turner (1994).

Stability Class	X Distance (km)	a	b
A	0.5 – 3.11	453.85	2.1166
	0.4 – 0.5	346.75	1.7283
	0.3 – 0.4	258.89	1.4094
	.25 – 0.3	217.41	1.2644
	0.2 – 0.25	179.52	1.1262
	0.15 – 0.2	170.22	1.0932
	0.1 – 0.15	158.08	1.0542
	< 0.1	122.8	0.9447
B	0.4 - 35	109.3	1.0971
	0.2 – 0.4	98.483	.98332
	< 0.2	90.673	0.93198
C	All X	61.141	0.91465
D	1 -3	32.093	0.64403
	0.3 - 1	32.093	0.81066
	< 0.3	34.459	0.86974
E	1 -2	21.628	0.7566
	0.3 - 1	21.628	0.7566
	0.1 – 0.3	23.331	0.81956
	< 0.1	24.26	0.8366
F	1 - 2	13.953	0.63227
	0.7 - 1	13.953	0.68465
	0.2 – 0.7	14.457	0.78407
	< 0.2	15.209	0.81558

The Gaussian dispersion equation (equation 5) is used to calculate a C_{10} value. The Y component is calculated using equation 4.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^{\,2}}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^{\,2}}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^{\,2}}\right)\right\} \qquad (5)$$

Where

- C = steady state concentration at a point (x,y,z) ($\mu g/m^3$),
- Q = emission rate ($\mu g/s$),
- u = average wind speed at stack height (m/s),
- y = horizontal distance from plume centerline (m),
- z = height of receptor with respect to ground (m),
- H = effective stack height ($H=h+\Delta h$, where h = physical stack height and Δh = plume rise)(m).

The emission rate used for this model was 2.85 g/s which corresponds to the total PM_{10} emission rate for a 20 bale per hour cotton gin based upon 1996 AP-42 emission factors. The source, located at $x_{source} = 0$ and $y_{source} = 0$, had a stack height set arbitrarily at 8 meters to approximate the exit height of a cyclone. The same source parameters were input to ISCST3 using BreezeISC (Trinity Consultants, 2002) and the same meteorological data for each day to determine the location of the maximum 24 hour average concentration. A polar receptor grid with 36 radials and 10 rings spaced at 100 meter intervals was used to locate the maximum 24 hour average concentrations. Once this location was determined, the receptor grid was removed and a single discrete receptor was placed in the location of the maximum 24 hour average concentration. The model was then repeated to obtain the 24 - C_{10} values from that particular day using ISCST3. The receptor location used in the ISCST3 model was then input to the spreadsheet model and the concentrations calculated.

The Hino – Power Law Model

The power law model is a commonly used model to determine concentrations for periods longer than 10 minutes (Cooper and Alley, 1994). The determination of longer time period averages is crucial to the permitting process for cotton gins because the average of 24 – C_{10} values will grossly over estimate the true concentrations. The Hino model (1968) suggests that the ratio of a 24 hour average concentration based upon 10 minute concentrations to that of one based on 60 minute concentrations is 2.5:1.

The power law model (Hino model) shown by equation 6 converts C_{10} values to C_{60} values using an exponent value or “P” value (Cooper and Alley, 1994).

$$C_t = C_{10} * \left(\frac{10}{t}\right)^P \qquad \text{Equation 6}$$

Where

- C_t = concentration from a time average of t minutes ($\mu g/m^3$),
- t = time period (minutes),
- P = p value used to convert the 10 minute concentration to C_t.

The p value is a function of source, stability class, and downwind distance X. The standard deviation of the wind direction is greatest in stability class A and least in stability class F. As the wind direction varies away from directly at the receptor, the measured concentration will decrease. Lower p values will result in less difference in the values of C_{10} and C_t (Stiggins, et al. 2002).

Solving equation 6 for P yields equation 7.

$$P = \frac{\ln\left(\frac{C_{60}}{C_{10}}\right)}{\ln\left(\frac{10}{60}\right)} \qquad (7)$$

A second spreadsheet model was developed using Monte Carlo simulation to develop a set of P value equations. These equations were dependent upon stability class and downwind distance X. The spreadsheet calculated C_{10} concentrations were based on an initial wind direction of 90 degrees. This initial wind direction was the direction of a wind blowing directly from the source to the receptor. The C_{10} value calculated using the initial wind direction was used as C_{10} in equation 7. The wind direction was simulated (Crystal Ball, 2002) based upon a normal distribution with the mean set at 90 degrees and the standard deviation corresponding to that published by the EPA (2000) depending upon stability class (see Table 3). For each of 5 distances (50, 100, 250, 500, 1000 meters), six C_{10} values were calculated and their average used as the value for C_{60} in equation 7. The P value was then calculated using equation 7. This process was repeated over 1600 times for each distance and stability class and the P values from each distance averaged to give a final P value.

Table 3. Standard deviations of horizontal wind direction variations by stability class reported by EPA (2000). It was assumed that wind direction variations were normally distributed.

Stability Class	**Range of Standard Deviation of Horizontal Wind Direction Fluctuations (degrees)**
1 (A)	> 22.5
2 (B)	17.5 – 22.5
3 (C)	12.5 – 17.5
4 (D)	7.5 – 12.5
5 (E)	3.8 – 7.5
6 (F)	< 3.8

The equations for the P values dependent upon stability class and downwind distance (x) were obtained by fitting a regression line to the data points found for each stability class. A second order polynomial equation was used in each case and yielded an R^2 value in excess of .99.

These new P value equations were then input to the original spreadsheet model and C_{60} values were determined based upon the original C_{10} values found by the Gaussian model.

Emission Factor Changes

The current emission factors from 1996 AP-42 for cotton gins are shown in Table 4. The percentage of TSP that is PM_{10} is assumed to be 39%. There exists an error in this assumption in that the true percentage of PM_{10} as demonstrated by Buser et al. (2002) is better approximated by a lognormal particle size distribution (PSD) with MMD = 18 and GSD = 2.2. Assuming these new PSD characteristics, the percentage of PM10 is reduced to 22.8%. A new list of emission factors based upon these new PSD characteristics was developed (see Table 5).

The efficiencies of cyclone abatement systems is perceived by most SAPRAs to be 90%. BBACT states that high efficiency cyclones (1D3D cyclones) are to be used on all centrifugal fan exhausts and at a minimum, covered condenser drums on all axial flow exhausts. Wang (2000) reported measured collection efficiencies for 1D2D and 1D3D cyclones over 98% efficient. Increasing the collection efficiency of cyclones from 90 to 98% would decrease the emission rate by a factor of 5. A more conservative increase to 95% would decrease the emission rates by a factor of 2. A new set of emission factors based upon the more conservative estimate of the true collection efficiency of cyclones was developed and is reported in Table 6.

Table 4. 1996 AP-42 emission factors for cotton gins. The emission factors assume that PM_{10} is 39% of TSP. CCD = covered condenser drum.

Process	**Abatement Device**	**TSP kg/bale**	**TSP lb/bale**	**PM_{10} kg/bale**	**PM_{10} lb/bale**
Unloading System	1D3D Cyclone	0.20	0.44	0.08	0.17
1st Stage Cleaner/Dryer	1D3D Cyclone	0.11	0.25	0.04	0.10
2nd Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.14	0.02	0.05
Trash Fan	1D3D Cyclone	0.02	0.05	0.01	0.02
Master Trash Fan	1D3D Cyclone	0.10	0.23	0.04	0.09
Overflow Fan	1D3D Cyclone	0.05	0.11	0.02	0.04
Mote Fan	1D3D Cyclone	0.12	0.27	0.05	0.11
First Stage Lint Cleaner	CCD	0.50	1.10	0.19	0.43
Second Stage Lint Cleaner	CCD	0.09	0.20	0.04	0.08
Battery Condenser	CCD	0.12	0.26	0.05	0.10
	Total	1.38	3.05	0.54	1.19

Table 5. 1996 AP-42 emission factors based upon a new PSD with MMD = 18 and GSD = 2.2. The mass fraction of TSP that is PM_{10} is 22.8%. CCD = covered condenser drum.

Process	**Abatement Device**	**TSP kg/bale**	**TSP lb/bale**	**PM_{10} kg/bale**	**PM_{10} lb/bale**
Unloading System	1D3D Cyclone	0.20	0.44	0.05	0.10
1st Stage Cleaner/Dryer	1D3D Cyclone	0.11	0.25	0.03	0.06
2nd Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.14	0.01	0.03
Trash Fan	1D3D Cyclone	0.02	0.05	0.01	0.01
Master Trash Fan	1D3D Cyclone	0.10	0.23	0.02	0.05
Overflow Fan	1D3D Cyclone	0.05	0.11	0.01	0.03
Mote Fan	1D3D Cyclone	0.12	0.27	0.03	0.06
First Stage Lint Cleaner	CCD	0.50	1.10	0.11	0.25
Second Stage Lint Cleaner	CCD	0.09	0.20	0.02	0.05
Battery Condenser	CCD	0.12	0.26	0.03	0.06
	Total	1.38	3.05	0.32	0.70

Table 6. 1996 AP-42 emission factors modified assuming 95% collection efficiency for all exhausts with cyclones as the abatement device. Note that in this scenario, all covered condenser drums have been replaced with 1D2D cyclones. PM_{10} is 39% of TSP.

Process	Abatement Device	TSP kg/bale	TSP lb/bale	PM_{10} kg/bale	PM_{10} lb/bale
Unloading System	1D3D Cyclone	0.10	0.22	0.04	0.09
1st Stage Cleaner/Dryer	1D3D Cyclone	0.06	0.13	0.02	0.05
2nd Stage Cleaner/Dryer	1D3D Cyclone	0.03	0.07	0.01	0.03
Trash Fan	1D3D Cyclone	0.01	0.03	0.00	0.01
Master Trash Fan	1D3D Cyclone	0.05	0.12	0.02	0.04
Overflow Fan	1D3D Cyclone	0.02	0.06	0.01	0.02
Mote Fan	1D3D Cyclone	0.06	0.14	0.02	0.05
First Stage Lint Cleaner	1D2D Cyclone	0.05	0.11	0.02	0.04
Second Stage Lint Cleaner	1D2D Cyclone	0.01	0.02	0.00	0.01
Battery Condenser	1D2D Cyclone	0.01	0.03	0.00	0.01
	Total	0.41	0.90	0.16	0.35

It should be noted that 1996 AP-42 only lists 8 process streams with a total TSP emission factor of 1.38 kg/bale (3.05 lb/bale). In this research, the 10 process streams used in 1988 AP-42 were also used. The total TSP emission rate from 1988 AP-42 was 1.013 kg/bale (2.24 lb/bale). The TSP emission factors from the ten process streams from 1988 AP-42 were multiplied by the ratio of the total 1996 AP-42 TSP emission factor to the total 1988 AP-42 TSP emission factor to get the modified 1996 AP-42 TSP emission factors used in this research (Buser, 2002).

To show the impacts of changing the emission rate on the dispersion modeling of low level agricultural point sources, the three different scenarios presented above were used to develop dispersion models in ISCST3. Three different ginning rates were modeled for each scenario, 20, 30, and 40 bales per hour. The same model setup was used for each scenario. The gin plant was 30 meters wide by 60 meters long and 12 meters tall placed in the center of a 500 by 500 meter property line boundary. A 2000 meter by 2000 meter uniform Cartesian receptor grid was used with receptors placed 100 meters apart. The meteorological data used in the models was for the period from October 15 through January 15 of 1988 from a county in south Texas. Building Profile Input Program (BPIP) was used to calculate the downwash for these models. Building downwash tends to increase on property concentrations due to wind wake effects on the down wind side of a structure (Trinity Consultants, 2000).

Results

The modified Stiggins method yielded a set of six equations (Table 7) that predict a P value as a function of stability class and down wind distance (X). These P value equations were then used to convert the C_{10} values predicted by ISCST3 to C_{60} values. The average over prediction for the 10 days of meteorological data used was 230%. Table 8 lists the concentrations predicted by the spreadsheet model, ISCST3, and the corrected C_{60} values with a corresponding C_{10} to C_{60} ratio.

Table 7. P value equations as a function of stability class and downwind distance X. The unit of X is meters.

Stability Class	**P value as a function of x**	**R^2**
A	$P = -1E\text{-}07x^2 + 0.0003x + 0.358$	0.992
B	$P = -1E\text{-}07x^2 + 0.0003x + 0.4112$	0.996
C	$P = -1E\text{-}07x^2 + 0.0003x + 0.4842$	0.996
D	$P = -1E\text{-}07x^2 + 0.0003x + 0.4908$	0.996
E	$P = -1E\text{-}07x^2 + 0.0002x + 0.3653$	0.995
F	$P = -6E\text{-}08x^2 + 0.0001x + 0.1517$	0.996

Table 8. Concentrations predicted by the Gaussian spreadsheet model (C_{10}), ISCST3 (C_{10}), and the corrected C_{60} values from the power law model.

	Spreadsheet C_{10}	**ISCST3 C_{10}**	**Power Law C_{60}**	**Ratio of C_{10} to C_{60}**
Day	**mg/m^3**	**mg/m^3**	**mg/m^3**	
1	559.8	558.7	243.9	2.29
2	323.2	323.2	147.7	2.19
3	625.1	625.0	255.6	2.44
4	405.1	405.2	166.2	2.44
5	385.8	385.8	188.0	2.05
6	312.0	312.0	142.0	2.20
7	491.1	491.1	196.4	2.50
8	421.3	421.3	193.0	2.18
9	579.9	579.8	251.4	2.31
10	497.4	497.3	209.5	2.37
			Average	2.30

The results of the highest 24 hour average modeled concentrations are shown in table 9. The models with lowered overall emission factors showed lower predicted concentrations than the original gin models using 1996 AP-42 emission factors. The decrease in modeled concentrations is directly proportional to the decrease in emission rate.

Table 9. Maximum ISCST3 predicted 24 hour average concentrations for three gin scenarios based upon 1996 AP-42 emission factors and modifications there of to reduce the emission factors. The increase in emission rate is directly proportional to the increase in gin through put capacity.

Model Scenario	Maximum 24 Hr. Average Concentration mg/m^3
20 BPH Original AP-42 Emission Factors	258.4
20 BPH New PSD (MMD=18, GSD=2.2)	138.9
20 BPH 95% Cyclone Collection Efficiency	71.1
30 BPH Original AP-42 Emission Factors	366.9
30 BPH New PSD (MMD=18, GSD=2.2)	211.8
30 BPH 95% Cyclone Collection Efficiency	105.3
40 BPH Original AP-42 Emission Factors	488.8
40 BPH New PSD (MMD=18, GSD=2.2)	282.5
40 BPH 95% Cyclone Collection Efficiency	140.2

Conclusions

The main intent of this paper was to demonstrate the impacts of the known errors currently associated with dispersion modeling. The Gaussian dispersion equation was used with the Pasquill-Gifford dispersion parameters σ_y and σ_z, as calculated by Turner (1994), to determine 10 minute average concentrations. It is assumed by the developers of ISCST3 that these C_{10} values are 60 minute average concentrations. The results from this research show that this assumption causes the over prediction of downwind concentrations by ISCST3 by an average factor of 2.3.

The over estimate of concentrations by ISCST3 directly impacts the operation of low level point sources such as cotton gins, feed mills, and grain elevators. Through this research it has been shown that a cotton gin, modeled by a SAPRA, could actually be in compliance with the NAAQS if the maximum 24 hour average PM_{10} concentration predicted by ISCST3 was 345μg/m^3. The development of the equations for P values as a function of stability class and downwind distance (X) help to support the previous findings of Stiggins, that reducing ISCST3 predicted concentrations by a factor of 2 yields a more accurate yet still conservative estimate of true 24 hour average concentrations.

The errors associated with the emission factors used in the modeling process also have a great impact on predicted concentrations. Predicted concentrations vary directly with changes to the emission rate. Changing the characteristics of the PSD of typical gin dusts from MMD = 12.6μm and GSD = 2.0 to MMD = 18μm and GSD = 2.2, will reduce the modeled concentrations by a factor of 1.7. Changing the collection efficiency value for high efficiency cyclones from 90% to a conservative 95%, will reduce the predicted concentrations by a factor of 3.5.

There are numerous examples of cotton gins that have been inappropriately regulated based upon the errors outlined in this paper. It has been demonstrated here that a few basic changes, based upon science, can have a great impact on the predicted downwind concentrations from low level point sources.

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