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Engineering Basis For Odor Dispersion Modeling - Part I: Preliminary Evaluation Of ISCST3 For Predicting Downwind Odors

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Abstract. *The description of odor concentrations is critical to odor dispersion modeling. In the literature, odor concentrations are characterized by odor units (OU), or odor units per cubic meter (OU/m^3). It is recommended that a more appropriate description of odor intensity as determined by dilution-to-threshold (DT) is OU. Units and protocols for odor modeling are discussed in this paper. Odor emission rates for area source modeling should have unit of OU*m/s, which will yield downwind odor concentrations in units of OU*

The US Environmental Protection Agency (EPA) approved ISCST3 Gaussian dispersion model was evaluated for odor modeling in predicting downwind concentrations and back calculating area source odor emission rates (flux). The comparison between ISC predicted downwind concentrations and field sampled downwind concentrations indicated that ISC can be used to predict average odor downwind concentrations, but failed to predict peak odor concentrations. ISC also had difficulty predicting downwind concentrations at wind speeds higher than 6 m/s. The comparison of odor emission rates between that obtained from back calculating using the ISC model with field sampled downwind odor concentrations and flux chamber source measurements show that flux chamber results for odor source sampling tended to under-estimate odor emission rates.

Keywords. Odor concentration, odor unit, OU, odor modeling, ISCST3, model evaluation.

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Introduction

The increased public concerns over odorous gas emission from large confined animal feeding operations (CAFO's) have resulted in a number of problems associated with regulation of odors in the United States (U.S.). These problems accentuate the need for additional study of odor mitigation and modeling. Currently atmospheric dispersion models are used as a tool to predict downwind pollutant concentrations, or to back-calculate average pollutant emission rates from downwind concentration measurements. Industrial Source Complex-Short Term, Version 3 (ISCST3) is the USEPA approved and recommended dispersion modeling program that is being used by most State Air Pollution Regulatory Agencies (SAPRAs) in the U.S. to estimate downwind concentrations of pollutants. A considerable amount of research has been done to improve this model accuracy for downwind particulate matter (PM) concentration predictions and back-calculated PM emission rate calculations. However, use of this model to predict odor emission from large animal feeding operations remains a challenge.

ISCST3 includes a set of Gaussian plume based models that can be used to predict downwind concentrations from point, line, and area sources. As pointed out by Smith (1993), there are number of important factors that cause difficulties when using Gaussian plume model techniques to predict downwind odor intensities. These factors are as follows:

1. Agricultural odor sources are near or at ground level;
2. Agricultural odor sources may be large area sources;
3. Maximum downwind concentration zones are close to the source of emissions;
4. Difficulty in odor source emission rate measurements; and
5. Spatial and temporal variations in source emissions.

Because of these challenges, evaluation of ISCST3 performance for downwind odor prediction requires a large amount of fieldwork. The objective of this paper is to report a quantitative examination of ISCST3 performance for fugitive odor emission with field sampling data. The final goal of this research is to address the problems associated with ISCST3 in application for odor modeling.

ISCST3 Gaussian Plume Models

ISCST3 Gaussian plume models for predicting downwind odor concentrations from point, line and area sources can be described by the following equations:

$$C = \frac{Q_P}{\pi \sigma_y \sigma_z u} \exp\left(-\frac{y^2}{2\sigma_y^2} \right) \exp\left(-\frac{H^2}{2\sigma_z^2} \right) \quad \text{(for point source)} \quad \text{........................ (Equation 1)}$$

$$C = \frac{2Q_L}{\sqrt{2\pi}\sigma_z u} \exp\left(-\frac{H^2}{2\sigma_z^2} \right) \quad \text{(for line source) .... (Equation 2)}$$

$$C = \frac{Q_A}{2\pi u} \int_X \frac{V}{\sigma_y \sigma_z} \left(\int_Y \exp\left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right] dy \right) dx \quad \text{(for area source) .... (Equation 3)}$$

where,

C = downwind odor concentration in odor units (OU),

Q_p = point source odor emission rate (OU*m^3/s),

Q_L = line source odor emission rate (OU*m^2/s),

Q_A = area source odor emission rate (OU* m/s),

σ_y, σ_z = Pasquill-Gifford plume spread parameters based on stability class,

u = average wind speed at pollutant release height (m/s),

H = effective height above ground of emission source (m),

V = vertical term used to describe vertical distribution of the plume,

X = upwind direction, and

Y = cross wind direction.

In order to model downwind odor concentrations, it is required to determine emission rate Q first. In this research, field source sampling was conducted to determine emission rates. On the other hand, ISCST3 can be used to back-calculate source emission rates (Q). To determine emission rate (Q in ISC), an initial emission rate Q_1 was used as input to determine an ISC modeled downwind concentration C_1 for given meteorological conditions. The emission rate Q_2 that matched field downwind concentration measurements was calculated by following equation:

$$\frac{Q_1}{Q_2} = \frac{C_1}{C_2} \quad \text{(Equation 4)}$$

where,

Q_1 = model initial emission rate corresponding initial modeled downwind concentration C_1, (OU*m/s for area source),

Q_2 = back-calculated emission rate corresponding specific field measured downwind concentration C_2, (OU*m/s for are source),

C_1 = initial downwind concentration, (OU), and

C_2 = field sampled downwind concentration.

Units for Odor Modeling

The description of odor concentrations and definition of odor units is critical to odor dispersion modeling. In the literature, odor concentrations are characterized as dilutions-to-threshold (DT) or odor unit (OU) by some researchers and as odor units per cubic meter (OU/m^3) by the others. According to Smith (1993), "The concentration of an odor in OU is the number of dilutions (of equal volume) required to reduce the concentration of the odor to the threshold of detection. This threshold is reached when 50% of a panel of people can just detect the odor (the other 50% cannot detect the odor). By definition, the concentration at the threshold is one OU". An OU is a dimensionless, relative measure of odor intensity, which is referred to by some as a concentration.

Currently, odor intensities of field samples are measured by human panelists and reported as odor units (OU) or detection thresholds (DT). In order to have consistent units for odor concentrations in OU between model predictions and field measurements, odor emission rates used in models (equations 1, 2 and 3) should be defined as OU*m^3/s, OU*m^2/s and OU*m/s for point, line and area sources, respectively (Smith, 1993).

Methodology

Figure 1 shows the protocol that was used to evaluate ISCST3 performance for odor dispersion modeling. It is also a protocol that is proposed here for odor dispersion modeling. ISCST3 with the graphical interface BreezeISC (Trinity Consultants, U.S.A.) was used to model downwind odor concentration reported as ISC predicted downwind odor concentration. Measured average area source emission rate in OU*m/s and simultaneous meteorological data (wind speed, wind direction, air temperature, etc.) were inputted into ISCST3 for modeling downwind odor concentration to compare with every field sampling result.

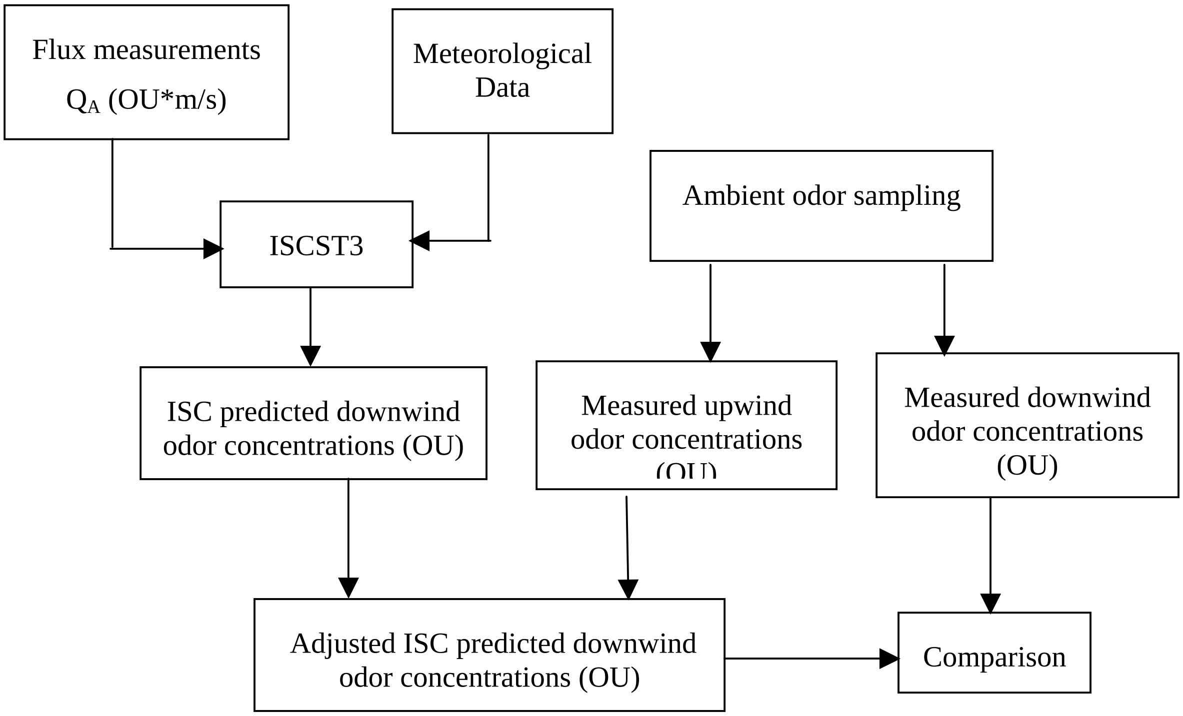

Figure 1. The protocol used to evaluate ISCST3 with field sampling measurements for odor modeling

ISC predicted downwind concentrations are affected only by the odor contribution from feedyard pen. In order to compare modeled downwind odor concentrations to field sampled downwind odor concentrations, ISC concentrations were adjusted to include upwind odor concentrations (pond odor emission when wind blew from northeast or southeast). Even though odor strength may not be additive, upwind odor concentrations were added into ISC predicted concentrations to obtain adjusted ISC downwind odor concentrations. This is the standard procedure when modeling PM emissions.

Ambient Odor Sampling

Ambient odor samples were collected from a commercial beef cattle feedyard in West Texas. Figure 2 illustrates the feedyard layout. Odor samples were collected in 10-L Teldar bags at a height of 1 m above the ground surface from immediately upwind and downwind from the feedyard pens. All the samples were analyzed for detection threshold (DT) within 24 hours at West Texas A&M University (Parker et al., 2003). Wind direction and speed were monitored by an onsite weather station. Upwind and downwind sampling locations were determined based upon wind direction determinations at the time of sampling.

An onsite weather station recorded meteorological data at one-minute intervals for all sampling days. These meteorological data were used to model downwind odor concentration at given emission rates.

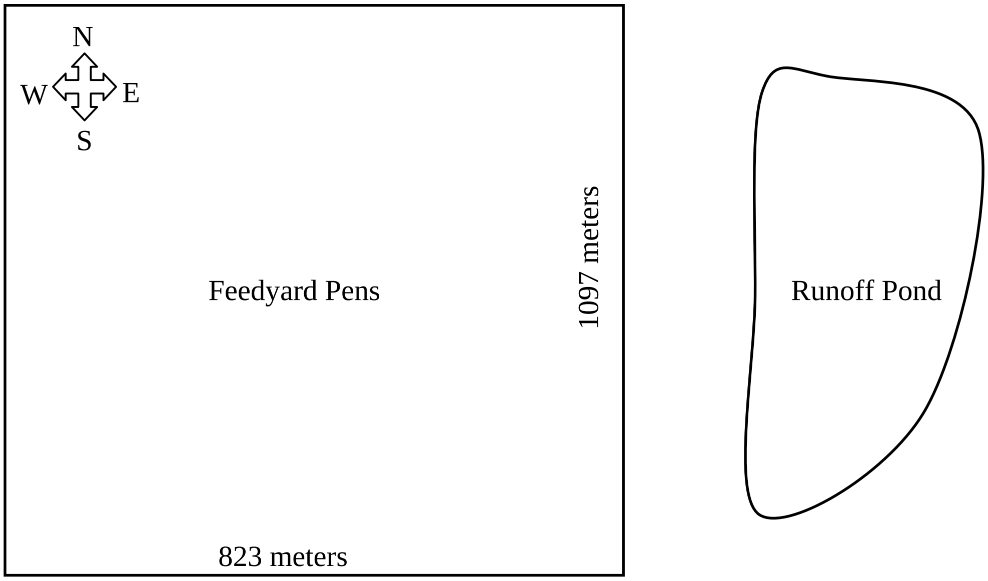

Figure 2. Layout of a commercial beef cattle feedyards at West Texas

Odor Source Sampling

A dynamic flow-through chamber was used for odor source sampling (see figure 3). This flux chamber consisted of a Lexan translucent cylindrical chamber (26.5cm I.D * 47.2 cm in height). (Park, et al., 2003, Baek et al., 2003 and Aneja et al. 2001). The chamber fits inside a stainless steel collar, which was driven into feedyard surface to a depth of 3 cm. Odor-free air was directed into the chamber at 11 to 14 L/min. Sample air was pulled from chamber into a 10-L Teldar bag for laboratory odor concentration analyses. The odor emission rate (or flux) was determined by the following equation:

$$J = \frac{q * [C]}{A} \quad \text{.. (Equation 5)}$$

where,

J = odor emission rate (flux) in OU*m/s for area source

q = air flow rate introduced to chamber in m^3/s

[C] = odor sample concentration measured by panelist in odor units (OU), and

A = surface area covered by the flux chamber in m^2.

Odor samples were collected three times over a two-week period in January 2004. The overall average emission rate was used to model downwind odor concentrations.

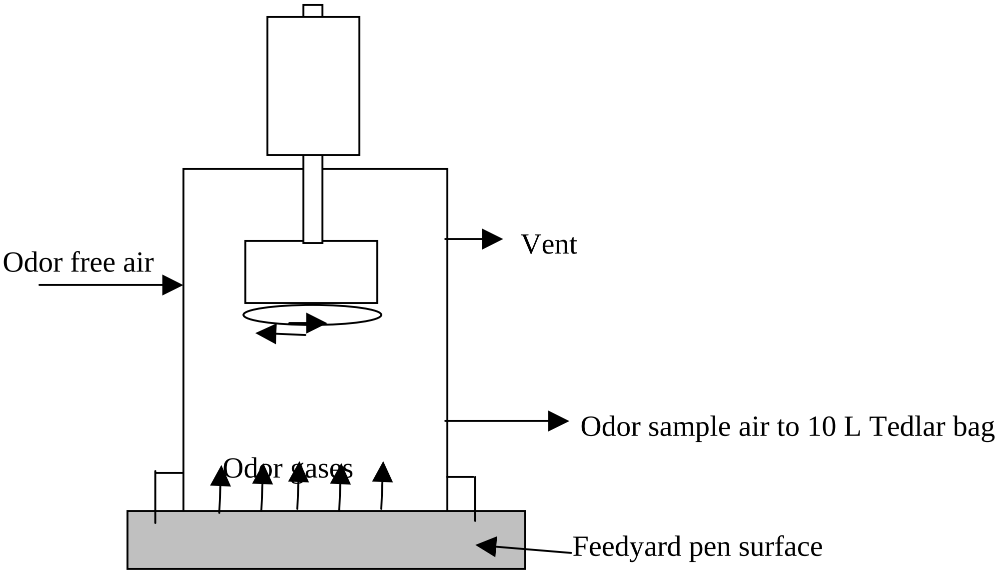

Figure 3. Dynamic flow-through chamber used for odor source sampling from a beef cattle feedyard pens at West Texas (Parker et al., 2003, Baek et al., 2003)

Results and Discussions

The odor source sampling results are listed in table 1. Equation 5 was used to calculate source emission rates from source sampling results. The surface odor emission rates are also listed in table 1. The overall average odor emission rate was 1.19 OU*m/s. This emission rate was used as input Q in the ISC to predict downwind odor concentrations in OU. Table 2 summarizes results of sampled downwind odor concentrations and modeled downwind odor concentrations. Since meteorological conditions are significant factors that impact downwind odor predictions, simultaneous wind speed and wind direction data are also listed in table 2 for analysis purposes.

Another application of modeling is to derive (back-calculate) source emissions from field concentration measurements. Table 3 lists back-calculated odor emission rates from feedyard pens. The simultaneously measured meteorological data were used in this modeling process. Subtracting sampled upwind concentrations from sampled downwind concentrations yields downwind concentrations as a consequence of emissions from feedyard pens. These downwind contributions were used as C_2 in equation 3 to derive emission rates from feedyard pens. Odor emissions are a function of many factors such as pen surface conditions (moisture content etc.), weather conditions, etc.. The results listed in table 3 indicate that odor emissions vary seasonally. The average emission rates derived through the modeling process (back-calculations) are higher than flux chamber sampled emission rates (see tables 1 and 3). The flux chamber protocol for odor source sampling tended to under-estimate odor emission rates. This could be a consequence of dilution with the high flow rate (14 l/min.) of odor-free air introduced into flux chamber.

Table 1. Measurement of odor emission rates from feedyard pen surface

Sampling Date	Chamber 1		Chamber 2		Chamber 3		Average ER (OU*m/s)
	PDT[a] (OU)	ER[b] (OU*m/s)	PDT (OU)	ER (OU*m/s)	PDT (OU)	ER (OU*m/s)	
01/29/2004	398.10	1.57	520.50	2.07	816.30	3.17	2.27
02/02/2004	385.70	1.16	275.60	0.82	250.70	0.75	0.91
020/5/2004	119.60	0.40	102.30	0.34	118.80	0.39	0.38
Average ER in OU*m/s							1.19

a. PDT: panel detection threshold in OU
b. ER: feedyard pen surface odor emission rate in OU*m/s

Table 2. Summary of sampled upwind and downwind odor concentrations (OU) versus ISC modeled downwind odor concentrations in odor unit (OU) utilizing an emission rate of 1.19 OU*m/s assuming a consistent odor emission rate over time

Sampling Date	WS[a] (m/s)	WD[b]	Sampled Upwind Odor Concentration[c] (OU)	Downwind Concentration (OU)		
				ISC[d] predicted	Adjusted ISC[e]	Sampled[f]
Day 1 - 06/03/2002	4.2	SW	11	10	21	91
Day 2 - 06/06/2002	4.3	SW	8	13	21	23
Day 3 - 06/13/2002	4.6	NE	23	9	31	27
Day 4 - 06/17/2002	5.0	S	11	8	20	14
Day 5 - 07/08/2002	4.4	SW	23	9	32	54
Day 6 - 07/11/2002	4.8	NE	16	12	28	54
Day 7 - 07/29/2002	5.4	SE	11	17	29	16
Day 8 - 08/12/2002	7.0	SW	11	8	20	30
Day 9 - 08/20/2002	4.8	SE	11	9	20	23
Day 10 - 08/21/2002	7.5	SW	7	8	15	45
Day 11 - 08/21/2002	6.0	SW	13	10	23	20
Day 12 - 08/22/2002	3.9	SW	8	15	22	17
Day 13 - 08/22/2002	3.5	SE	13	12	25	34
Day 14 - 09/09/2002	5.6	SE	13	11	23	25
Day 15 - 10/07/2002	4.4	SE	16	13	29	27
Day 16 - 10/30/2002	5.8	NE	16	10	26	665
Day 17 - 11/04/2002	4.0	SE	16	15	31	35
Day 18 - 11/13/2002	8.1	SW	25	11	36	99
Day 19 - 12/16/2002	2.3	SE	32	17	49	49
Day 20 - 01/06/2003	3.7	NE	21	16	37	23
Day 21 - 01/20/2003	6.2	NW	14	9	22	50
Day 22 - 01/22/2003	3.7	NE	59	16	74	83
Day 23 - 02/17/2003	6.3	SW	32	9	41	64
Day 24 - 03/03/2003	7.9	SW	12	7	19	19

a. Wind speed at sampling time.
b. Wind direction at sampling time is the direction that wind blew from.
c. Sampled upwind odor concentrations were sampled immediately upwind from feedyard pens.
d. ISC predicted downwind odor concentrations at approximately the field sampling time.
e. Adjusted ISC downwind odor concentrations = ISC predicted downwind concentrations + sampled upwind odor concentrations.
f. Sampled downwind odor concentrations were sampled immediately downwind from feedyard pens.

Table 3. Back-calculated odor emission rates ($ER_{modeled}$) from feedyard pens by using ISCST3 and sampled downwind odor concentrations contributed only by feedyard pens. The feedyard pen odor concentrations were the sampled downwind concentrations minus upwind concentrations.

Sampling Date	$ER_{modeled}$ (OU*m/s)	Sampling Date	$ER_{modeled}$ (OU*m/s)
Day 1 - 06/03/2002	9.63	Day 13 - 08/22/2002	2.14
Day 2 - 06/06/2002	1.35	Day 14 - 09/09/2002	1.39
Day 3 - 06/13/2002	0.59	Day 15 - 10/07/2002	0.97
Day 4 - 06/17/2002	0.43	Day 16 - 10/30/2002	77.6
Day 5 - 07/08/2002	4.09	Day 17 - 11/04/2002	1.55
Day 6 - 07/11/2002	3.71	Day 18 - 11/13/2002	7.76
Day 7 - 07/29/2002	0.32	Day 19 - 12/16/2002	1.23
Day 8 - 08/12/2002	2.61	Day 20 - 01/06/2003	0.14
Day 9 - 08/20/2002	1.56	Day 21 - 01/20/2003	5.07
Day 10 - 08/21/2002	5.81	Day 22 - 01/22/2003	1.85
Day 11 - 08/21/2002	0.81	Day 23 - 02/17/2003	4.31
Day 12 - 08/22/2002	0.77	Day 24 - 03/03/2003	1.14
		Average	5.70

Figures 4, 5 and 6 show the comparison of downwind odor concentrations from ISC modeling, adjusted ISC concentrations (including the upwind with the modeled results), and field sampling measurements. Figure 4 illustrates this comparison sorted by wind speed in ascending order, whereas figure 5 shows this comparison sorted by downwind concentration in ascending order. These comparisons illustrate that the ISC process (not including upwind concentrations) under-predicted downwind odor concentrations in every case. The adjusted ISC process with upwind odor concentrations added to the modeled results compared to field-sampled results in figure 4 indicate that ISC modeling can fairly well predict downwind odor concentrations. However, the comparison illustrated in figure 5 shows a trend that adjusted ISC downwind concentrations are less than measured concentrations for wind speeds higher than 6 m/s. Also, adjusted ISC downwind concentration results tend to be less than measured concentrations at the high concentrations (see figure 6). One of the most important observations from the comparison is that ISC failed to predict peak concentrations. There several reasons causing ISC to under-predict downwind odor concentrations:

1. ISC predicted one hour average downwind concentrations, whereas, the sampled results were instantaneous odor concentration measurements.

2. Odor source emissions vary with many factors such as temperature, surface moisture, season, etc. The constant average emission rate used in the model yields average downwind predictions, which might not match instantaneous downwind odor intensity as a function of time. More accurate emission rates should be used for different weather and surface condition.

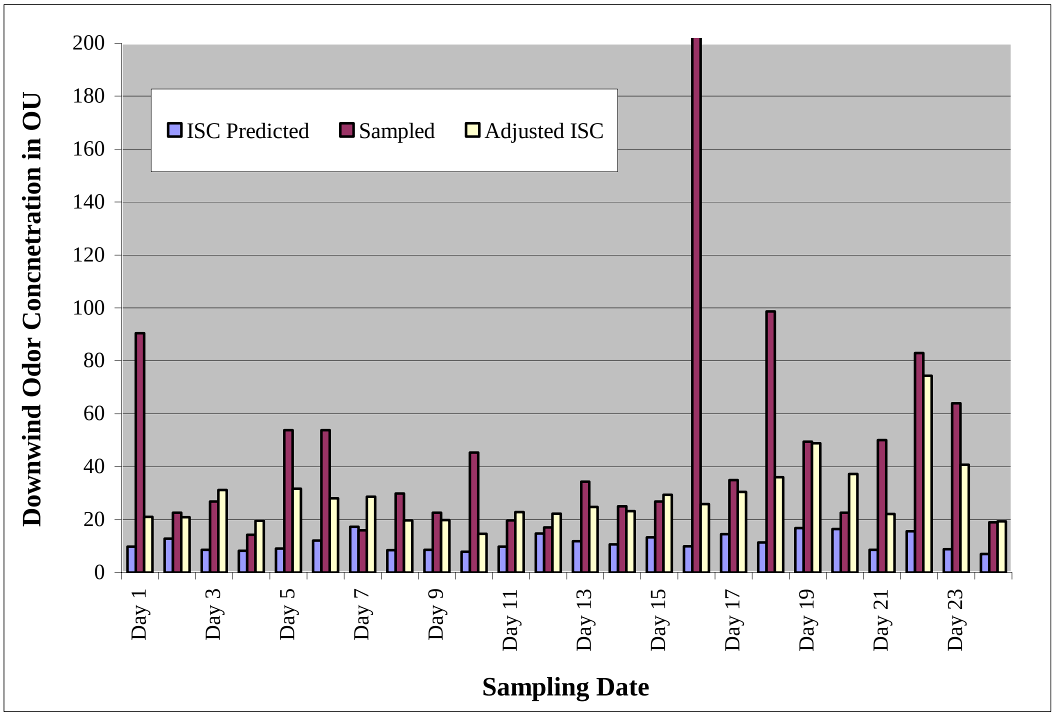

Figure 4. Comparison of downwind odor concentration

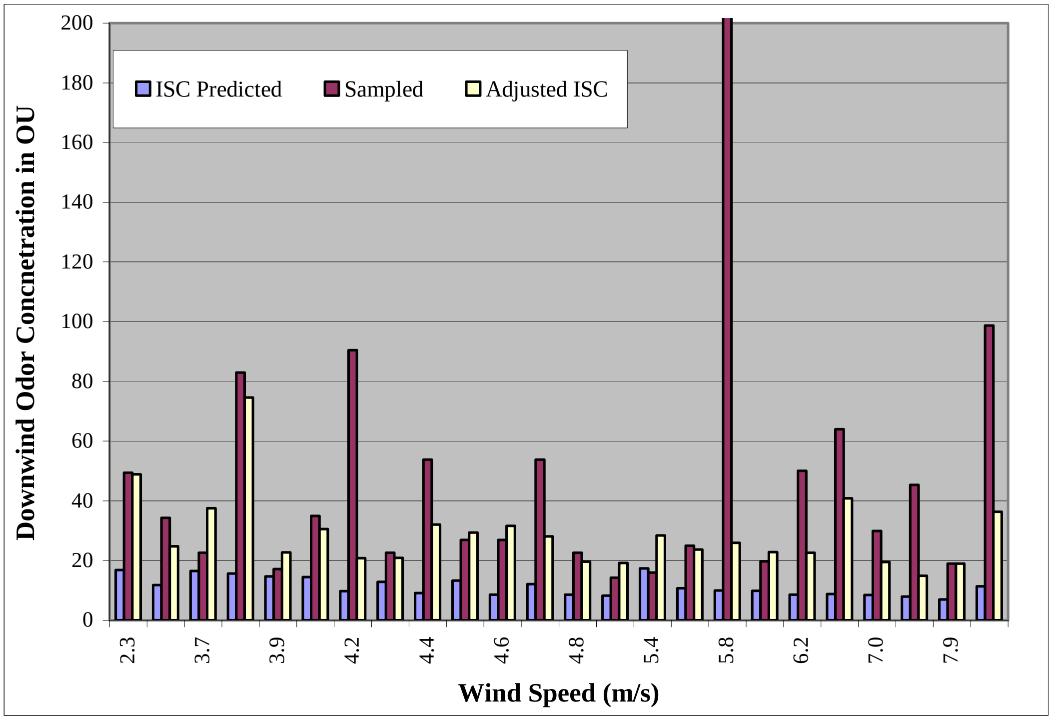

Figure 5. Comparison of downwind odor concentration sorted by wind speed in an ascending order

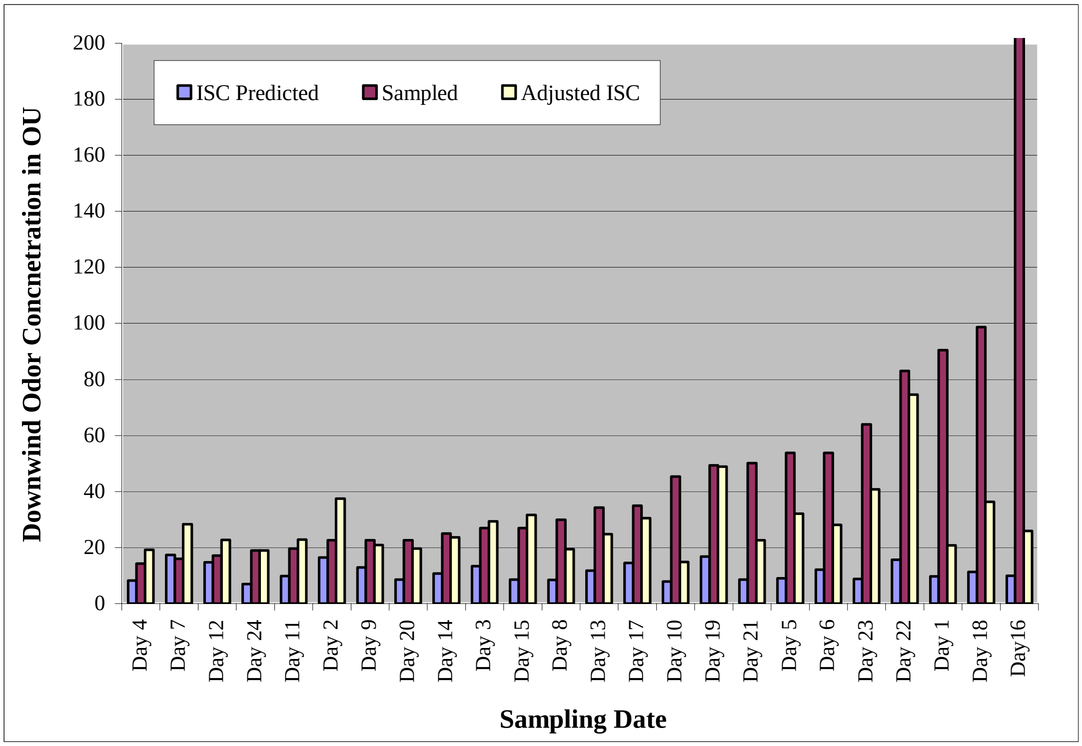

Figure 6. Comparison of downwind odor concentration sorted by downwind concentration in an ascending order

Conclusion

The description of odor concentrations is critical to odor dispersion modeling. In the literature, odor concentrations are characterized by odor units (OU), or odor units per cubic meter (OU/m^3). It is recommended that a more appropriate description of odor intensity as determined by dilution-to-threshold (DT) is OU. Units and protocols for odor modeling are discussed in this paper. Odor emission rates for area source modeling should have unit of OU*m/s, which will yield downwind odor concentrations in unit of OU.

The US EPA approved ISCST3 Gaussian dispersion model was evaluated for odor modeling in predicting downwind concentrations and back-calculating area source odor emission rates. The comparison between ISC predicted downwind concentrations and field-sampled downwind concentration measurements indicated that ISC could be used to fairly well predict average odor downwind concentrations. However, the ISC adjusted modeling results tended to predict concentrations less than the measured concentrations for high wind speeds (greater than 6 m/s) and high concentrations. The modeled concentrations failed to predict peak odor concentrations. The comparison of odor emission rates obtained by back-calculating fluxes using ISC modeling with field measurements of downwind odor concentrations and flux chamber source sampling results show that the flux chamber protocol tended to under-estimate odor emission rates.

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