EVALUATION OF COMMERCIAL AIR DISPERSION MODELS FOR LIVESTOCK ODOUR DISPERSION SIMULATION

A Thesis Submitted to the College of
Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of Master of Science
In the Department of Agricultural and Bioresource Engineering
University of Saskatchewan
Saskatoon

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ABSTRACT

The public nuisance and health concerns caused by odours from livestock facilities are among the key issues that affect neighbouring communities and the growth of the livestock industry across Canada. A setback distance is the common regulatory practice to reduce odour impact on the neighbouring areas. The air dispersion modeling method may be a more accurate tool for establishing setback distances since it considers site-specific airborne emissions, such as odour and gases from the animal production site as well as weather conditions and then estimates a concentration of the pollutant (odour, ammonia, etc.). Although various dispersion models have been studied to predict odour concentration from agricultural sources, limited field data exist to evaluate their applicability in agricultural odour dispersion. Thus, the purpose of this project was to evaluate the selected commercial air dispersion models with field plume measurements from swine operations.

Firstly, this thesis describes a sensitivity analysis of how the climatic parameters affect model simulations for four selected air dispersion models, ISCST3, AUSPLUME, CALPUFF, and CALPUFF. Under the steady state weather condition, mixing height had no effect on the livestock odour dispersion, while atmospheric stability, wind speed and wind direction had great effect on the livestock odour dispersion. Ambient temperature had a moderate effect compared with other parameters. Under variable weather conditions, the predicted odour concentrations were much lower than the results under steady state weather conditions.

A series of comparisons between model predictions of the same four models and field odour measurements were conducted. When using the livestock odour plume measurement data from University of Manitoba, three equations were used to convert the model predicted odour concentration to field measured odour intensity. The equations did not predict odour intensity very well. No model showed obvious better performance than the others. Scaling factors did not improve the results considerably. When using the odour plume measurement data from University of Minnesota, INPUFF2 perfomed better than CALPUFF. Scaling factors did improve the modeled results. When using the odour plume measurement data from University of Saskatchewan, INPUFF2 also performed better than CALPUFF. Scaling factors were still useful for the results improvements.

Finally, because CALPUFF is the US EPA preferred model and predicted the highest values under variable weather conditions in the sensitivity study, we used it to simulate odour plumes on selected three swine sites using hourly weather data from 1993 to 2002 in Yorkton, Saskatchewan. The maximum predicted distance was 2.9 km for 1 OU, which was lower than the recommended maximum setback distance of 3.2 km.

It is recommended that the variable weather conditions be used in the setback distance determination. CALPUFF is the preferred model and INPUFF2 is another option for field odour plume simulation, however scaling factors are needed to bring the model predictions close to the field measured results. Because the models evaluated were not developed for odour dispersion simulation, a model that can accurately predict livestock odour dispersion should be developed to take into account of the difference between odour and gas and wind direction shifts within the simulation time interval.

ACKNOWLEDGEMENTS

I first and foremost express my sincere gratitude and appreciation to my research supervisor, Dr. Huiqing Guo, for her valuable guidance, advice, criticism and encouragement throughout the course of this research work and in the preparation of this thesis. I also express sincere thanks to my co-supervisor, Dr. John Feddes, for his thoughtful pieces of advice, support and wealth of experience have made this work a great success. My acknowledgements also go to the Advisory Committee members, Dr. Bernardo Predicala, and Dr. Stan Shewchuk, for their valuable comments and suggestion in the preparation of this thesis. I would also like to thank Professor WJ Chris Zhang for acting as my external examiner.

I am grateful to my parents, Guishen Xing and Yuzhi Li in China for their constant support and encouragement. I wish to gratefully acknowledge the inspiration, encouragement and consistent help in many ways received from my brother Minghai Xing, and sister-in-law Qiutong Chen throughout my graduate studies. Sincere thanks are also extended to Dr. Jude Liu, Dr. Jifeng Ying, Zimu Yu, Xue Li, Yongxin Li, Lifang Liu, Xiangling Wang and Jing Bai for sharing their time with me.

I thankfully acknowledge the financial assistance by the NSERC, Saskatchewan Agriculture Development Fund, Saskatchewan Pork, and Alberta Livestock Industry Development Fund Ltd., and Environment Canada and field plume measurement data assistance provided by University of Manitoba, University of Alberta, University of Minnesota, and University of Saskatchewan.

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List of Abbreviations

ADMS	Atmospheric Dispersion modelling System
AERMOD	American Meteorological Society / Environmental Protection Agency Regulatory Model
AODM	Austrian Odour Dispersion Model
ASTM	American Society of Testing and Materials
Australian EPA	Australia Environmental Protection Authority
AUSPLUME	Australian Plume Model
CALPUFF	Lagrangian California Puff Model
C5	Atmospheric stability C (slightly unstable) with wind speed 5 m/s
D5	Atmospheric stability D (neutral) with wind speed 5 m/s
D8	Atmospheric stability D (neutral) with wind speed 8 m/s
E3	Atmospheric stability E (slightly stable) with wind speed 3 m/s
E5	Atmospheric stability E (slightly stable) with wind speed 5 m/s
EMS	Earth Manure Storage
F1	Atmospheric stability F (moderately stable) with wind speed 1 m/s
F3	Atmospheric stability F (moderately stable) with wind speed 3 m/s
FB	Fractional Bias
GPS	Global Positioning System
h	hour
INPUFF2	Integrated PUFF version 2
ISC	Industrial Source Complex
ISCST3	Industrial Source Complex Short Term version 3
MDS-II	Ontario’s Minimum Distance Separation guidelines
NMSE	Normalized Mean Square Error
NPSC	Negative Pressure Synthetic Covers
NSERC	Natural Sciences and Engineering Research Council
OB	Observed
OFFSET	Odour From Feedlots Setback Estimation Tool
OU	Odour Unit
OU/m^3	Odour Units per cubic meter
P-G	Pasquill-Gifford
PR	Predicted

S	South
SRDT	Solar Radiation Delta-T
SW	South-West
TAPM	The Air Pollution Model
US EPA	Environment Protection Agency of the United States
W	west
WNW	West-North-West

1. INTRODUCTION

Odour nuisance complaints against animal production farms have been increasing rapidly in the last decade and are becoming one of the major barriers for further development of the livestock industry (Guo et al., 2004). Solutions for the problem frequently involve the specification of setback distances from neighbouring properties; however, most of the existing setback guidelines were determined either by individual judgement and experience or by a combination of neighbour surveys and odour measurement, instead of calculations of dispersion models (Guo et al., 2004). They pointed out that the impact of odours on the surrounding neighbors and communities depends on the amount of odour emitted from the site, the distance from the site, weather conditions, topography, and odour sensitivity and tolerance of the neighbors. The establishment of science-based setback distances requires an accurate understanding of these factors. Since air dispersion models consider site-specific airborne emissions, such as odour and gases from the animal production site as well as weather conditions and then estimate a concentration of the pollutant (odour, ammonia, etc.), using air dispersion models to predict downwind livestock odour concentration in order to establish science-based setback distances has the potential to become a common practice for regulatory agencies.

In 1980, Keddie (1980) used a Gaussian model ISC (Industrial Source Complex) to simulate odour dispersion from agricultural sources for the first time. Since then, air dispersion models have become a tool to estimate downwind odour concentrations from agricultural odour sources (Keddie, 1980; Janni, 1982; Carney and Dodd, 1989; Mejer and Krause, 1985; Lorimer, 1986; Ormerod, 1991; Mcphail, 1991; Gassman, 1993; Chen et al., 1998, Zhu et al, 2000, Guo et al., 2001, Koppol et al., 2002; Jacques Whitford Ltd, 2003; Bjerg et al., 2004). Although most commercially available air dispersion models are originally designed for industrial sources, they have been validated in predicting odour concentrations downwind from agricultural sources (Zhu et al., 2000; Guo et al., 2001; Sheridan et al., 2004; Jacques Whitford Environment Ltd., 2003). The application of dispersion models for odour dispersion from livestock production site is popular, however, little research has been done to compare the different models' simulation results so that we do not know which model is more suitable for odour dispersion simulation from livestock farms than others. Using air dispersion models to predict livestock facility odours hinges on the validation of models, which requires a large amount of field work and wealth of data (Zhu et al., 2000). However, the lack of experimental data to quantitatively examine the performance of air dispersion models has become the major obstacle in using these models to predict odours from agricultural sources. With some field data obtained by University of Manitoba, University of Minnesota, and University of Saskatchewan in the last several years, it has become possible to compare and evaluate the performance of the commercial dispersion models. The present project is intended to validate four commercial air dispersion models for odour dispersion by comparing the field data with model data and provide recommendations regarding model selection and method for adapting the models in livestock odour dispersion predictions.

2. LITERATURE REVIEW

2.1 Odour Setback Distance Guide Overview

Odour is diluted as it is transported in the atmosphere. If there is proper distance between the odour source and the neighbouring residents, the odour nuisance may be minimized. Setback distance is defined as the "separation distance between livestock buildings/facilities and residential areas" by Schauberge et al. (2002). Figure 3.1 is a diagram that illustrates the need for setback distances. Setback distances widen the gap between source and receptor and hence allow the atmospheric mixing process time to sufficiently dilute the emission products. The separation is specifically put in place to a minimum distance and separate or reduce the odour annoyance within the community (Shewchuk et al., 2006). They pointed out that science-based separation distances are needed to provide for the overall sustainability of agriculture in Canada.

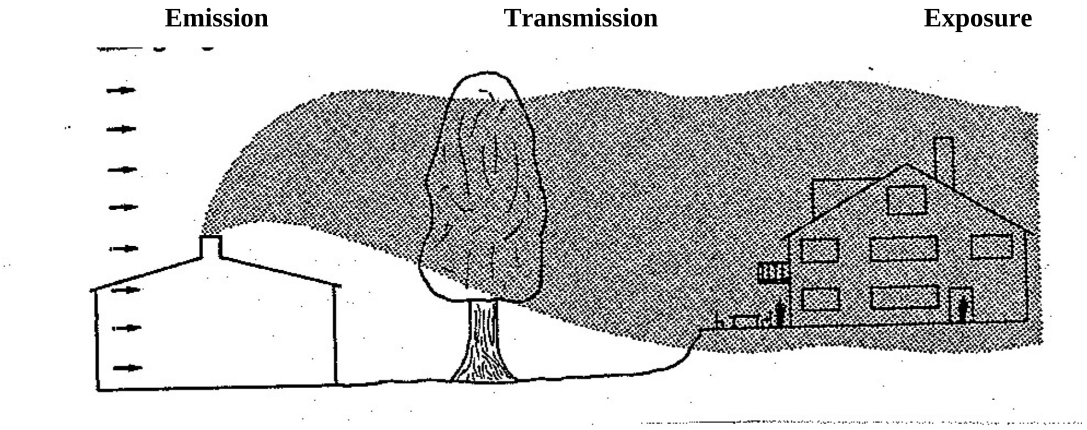


Figure 2.1 Emission, transmission and exposure of the community to agriculture intensive livestock facilities (Shewchuk et al., 2006)

However, the determination of odour-based setbacks for livestock facilities is a difficult and complex problem. Mahin (2001) suggests that there are 5 types of approaches that are commonly used to determine the setback distance from sites with agricultural odour sources. Briefly these are:

1. General regulations prohibiting nuisance or annoyance conditions as determined by field inspectors.
2. Setback distances that are based only on the number and type of animals and receptors.
3. Setback distances that are based on the number and type of animals but also include the empirical formulae and factors for type of manure handling systems, terrain, animal feed, etc.
4. Ambient air concentration limits for compounds such as hydrogen sulphide and ammonia.
5. Set back distances determined by dispersion models that are based on odour emission rates of the sources and down wind odour concentrations.

Most of the existing setback distances are determined either by individual judgement and experience or by a combination of neighbour surveys and odour measurement, instead of calculations by dispersion models (Guo et al., 2004). It is becoming more common now to use atmospheric dispersion models to predict where odour nuisance is likely to occur near animal production facilities. This approach has many advantages in that emissions can be modelled for different scenarios. There are several models that are commercially available and often, particular models are favoured in different parts of the world. A problem has been the lack of peer-reviewed data on model validation, particularly regarding odour (Curran et al., 2002). Differences in model outputs can be critical especially if the result is used to determine setback distances and abatement techniques as part of a regulatory framework.

Guo et al. (2004) compared five existing setback models, Austrian model, Ontario's Minimum Distance Separation guidelines (MDS-II) model, Purdue model, W-T model, and Minnesota's OFFSET model, when used on 13 existing swine farms. These models were selected in this study because they were considered to be representative of setback models generated by various methods as described above. After the comparison, the difference might be as much as ten times between the closest and farthest setback distances determined by different models, therefore, it is critical that a suitable model is chosen and the information into the components of the model is known, especially if used by local government units or others for land use decision-making.

2.2 Livestock Odour

2.2.1 Livestock Odour Characteristics

When the odour were emitted from the livestock facility, it is necessary to measure and describe the odour to assess the impact on the neighbouring land users situated around the operations. Odours can be characterized in five ways. Each parameter adds to the complete description of an odour. They are: Concentration, Intensity, Persistence, Hedonic tone, and Character descriptor. Odour concentration and intensity are the two most common parameters measured. During the work of evaluation for the air dispersion models, the air dispersion models can only predict the odour concentration while odour intensity record is employed in the field measurement, so if we compare these two sets of data, conversion equation between odour concentration and intensity is needed. .The other three – persistence, hedonic tone and character descriptors – are commonly viewed as more subjective measurements and are not typically used for scientific or regulatory purposes.

Odour concentration, measured by olfactometry is expressed as "odour units" (OU) (mostly in North America) or "odour units per cubic meter"(OU_E/m^3) (in Europe). This is a non-analytical technique employing the human olfactory sense to measure the strength of odours since the previous research showed that there is no established correlation between the concentrations of individual odourants in odour or specific groups of odourants and the human response to odour (Jones et al., 1994). In this technique, odour samples are diluted with different, known volumes of a neutral, odourless gas (diluents), e.g., nitrogen or filtered air. The different mixtures of odour and diluents are presented to a human panelist or group of panelists for sniffing and their responses are recorded (NCMAWM, 2001; Jiang, 2000; CEN, 1999). The dilution threshold is established when 50% of the panelists have correctly identified the odorous sample from the odour free samples (Choiniere and Barrington, 1998). A regression analysis is performed and the dilution ratio corresponding to 50% of the correct responses is regarded as the odour concentration. Schmidt (2002) defines "odour units" as the volume of diluents required to dilute a unit volume of odour until the detection threshold of the odour is obtained. Alternatively, "odour units per cubic meter" is defined as the concentration of odour in one cubic meter of air at the panel detection threshold of the odour (NCMAWM, 2001; CEN, 1999). Air dispersion models use mass emission rate in g/s from a source, however, odour emission rate takes the form of OU/s. When using air dispersion models in this study, the mass of odour in term of OU is considered equivalent to the mass of gas in g. Therefore, odour concentration in OU/m^3 was considered equivalent to mass concentration in g/m^3 which is used with the air contaminant concentration output of all models while odour emission rate from a source in OU/s was equivalent to mass emission rate in g/s from a source (Williams, 1985; Carney and Dodd, 1989; Pain et al., 1991; Mahin, 1997; Zhu et al. 1998; Zhu et al., 2000; Guo et al., 2001; Zhang et al., 2002; Zhang et al., 2003; Zhang et al., 2005).

Odour intensity describes the strength of an odour sample. It is measured by relating the perceived concentration of an odour to those of a memorized range of concentrations of a known reference substance, in most cases n-butanol. Intensity can be measured against a five-step or eight-step scale using n-butanol, a standard reference chemical (ASTM, 1999). Trained panellists sniff containers of n-butanol at different concentrations in water to learn the scale. They then are presented diluted or full-strength (diluted is always presented first) odourous air samples that the panellist rate against the n-butanol scale. Measurements typically occur in the field, at locations downwind from the source(s) of odour(s). In general, one limitation to the accuracy of this technique is the level of variability in the measurements. Variability may be partly attributed to differences between the human olfactory responses to n-butanol in water comparison to the response to odours, specifically livestock odours. It may also result, in part, to differences between panellist measurements through the use of unscreened human subjects as odour assessors**.**

2.2.2 Relationship between Odour Concentration and Odour Intensity

To evaluate the air dispersion models, it is necessary to compare the model's predictions with the field measurements. The models' output is the odour concentration while the odour intensity is presented in the field measurements. Thus, it is necessary to determine the relationship between odour concentration and odour intensity so that comparison can be made between data collected in the field and generated by the model. In order to determine the relationship between these two variables, air samples collected from the field need to be measured for both odour concentration and odour intensity by trained panellists in the laboratory. Bundy et al, (1997) and Nicolai et al. (2000) evaluated three models for presenting the odour concentration and intensity relationship.

The Weber-Fechner law model:

$$I = K_1 \log C + K_2 \tag{2.1}$$

where I is the perceived intensity and C is the corresponding threshold odour concentration, and k_1 and k_2 are constants.

The Stevens model:

$$I = k_1 C^{k_2} \tag{2.2}$$

The Beidler model:

$$I = \frac{K_1 K_2 C}{1 + K_2 C} \tag{2.3}$$

The conclusion was that the Weber-Fechner law model gave the best fit for odour data collected from pig buildings and manure storage units. In Zhu et al. (2000), air samples collected from the field were analyzed for both odour threshold and odour intensity (on a scale of 0 to 5) in the laboratory to find the relationship between these two variables. The relationship between odour concentration and intensity for all the distances and sources from University of Minnesota is

$$\text{n - butanol equivalent (ppm)} = 83.333 \times \exp(1.0986 \times \text{I}) \tag{2.4}$$

and $C = 0.0139 \times \text{n - butanol equivalent (ppm)}^{1.2591}$ (R^2=0.87) (2.5)

where I= odour intensity on a 0 to 5 scale (I=0 to 5), C = odour concentration (OU/m^3).

In Guo et al. (2001), 124 odour samples were collected from 60 swine buildings and 66 swine manure storage facilities, and 55 odour samples collected at 10 dairy and beef farms in Minnesota during 1998 and 1999. These samples were measured for odour intensity and concentration by trained panelists in the Olfactometry Laboratory. The relationships between odour intensity 0 to 5 scales and concentration are expressed as:

swine odours: $I = 0.93\ln(C) - 1.976$ (R^2=0.69) (2.6)

cattle odours: $I = 0.93\ln(C) - 2.068$ (R^2=0.89) (2.7)

According to Zhang et al. (2005), the conversion equation from University of Manitoba based on the lab measurement of odour concentration and intensity takes the form of

$I = 1.43\ln(C) + 0.78$ (R^2=0.61) (2.8)

while the University of Alberta based on a recent study, the relationship between the perceived intensity of the headspace of standard 60-mL training jars containing n-butanol concentration (ppm) of the 8-point odour intensity referencing scale measured by odour sniffers and the corresponding n-butanol concentration (OU/m^3) determined by an olfactometer (Segura and

Feddes, 2005). The results from this study were used to as the conversion equation represents the University of Alberta. The equation is

$$I = 1.245\ln(C) - 0.046 \quad (R^2=0.79) \qquad (2.9)$$

where I= odour intensity of n-butanol on a 0 to 8 scale, C = odour concentration of n-butanol (OU/m^3).

Equation 2.6 – 2.9 will be used for the following data analysis about the comparison of model prediction with nasal ranger's odour plume field measurement data.

2.3 Odour Dispersion

Odour dispersion results from turbulence which is the local fluctuation in the wind flow and the instantaneous concentration downwind of the source(s) varies continuously with the turbulence in the wind. Odour emitted into the atmosphere is transported and diluted away from a source by turbulent fluctuations. Turbulent eddies have a range of sizes, small eddies on the order of a centimetre, to very large scale eddies, tens of meters across (Shewchuk et al., 2006). They pointed out when there is a continuous plume from a source of odours or pollutants, for example, the smaller eddies in the atmosphere (i.e., smaller than the size of the plume) work to expand the plume around its centre, diluting the plume internally as it travels downwind. Larger-scale atmospheric eddies work to transport the plume bodily, primarily in the crosswind and vertical directions (meander), while providing little in the way of dilution (Shewchuk et al., 2006). In between, eddies equivalent to the size of the plume both dilute and transport the plume.

If the effects of plume spread and meandering are viewed at a fixed location, such as a concentration sampling location, the sampling monitor might register periods of turbulent concentration fluctuations as a plume travels past the monitor, and periods of zero concentration, or intermittency, if the plume meanders away from the monitor (Shewchuk et al., 2006). Based upon these observations, the dispersion of the plume can sometimes be viewed as the result of two distinct processes: the instantaneous spreading out of the plume in the vertical and crosswind directions (from the small eddy turbulence) and the meandering or fluctuation of the entire plume about its mean position as it travels downwind (from the large-scale eddy turbulence) (Shewchuk et al., 2006).

The ability of the atmosphere to disperse odour depends on the wind direction, the strength of the emission, the terrain characteristics, as well as wind speed and atmospheric stability (Jacques Whitford Environment Ltd., 2003).

Atmospheric stability is the ability of the atmosphere to resist vertical motion or to suppress or enhance turbulence. It can be broadly classified as being stable, unstable or neutral. Pasquill (1961) developed a method for calculating the stability categories from knowledge of the wind speed, solar radiation and cloud coverage. These stability categories A, B, C, D, E and F are shown in Table 3.1.

Table 2.1 Pasquill stability categories

Wind speed (m/s)	Daytime(excluding 1 h before sunset and 1 h after sunrise)Incoming solar radiation (mW/cm^2)				Within 1 h of sunset or sunrise	Night time cloud amount (oktas)		
	Strong >60	Moderate 30-60	Slight <30			0-3	4-7	8
<2	A	A-B	B	C	D	F	F	D
2-3	A-B	B	C	C	D	F	E	D
3-5	B	B-C	C	C	D	E	D	D
5-6	C	C-D	D	D	D	D	D	D
>6	C	D	D	D	D	D	D	D

When the atmosphere is stable (stability class F), there is minimal atmospheric turbulence, and hence little dispersion. Unstable atmosphere can cause strong winds that result in mechanical turbulence due to interactions of the wind with the ground and obstruction such as trees and buildings. The mechanical turbulence results in increased dispersion.

Zhu (1999) illustrated the effects of stability classes on the performance of air dispersion models in predicting agricultural odour transport when an air dispersion model (INPUFF-2), developed by US EPA based on the Gaussian model theory, are used. He pointed out that at distances close to the source (within 200 m), unstable and neutral stability categories will give higher odour numbers, while at distances farther than 200 m, stable conditions will yield higher odour levels. He also pointed out that the plume width of agricultural odours varies with the stability classes, which is different from the common observation of using Gaussian models to predict strong industrial pollutants. He also concluded that Gaussian models can not predict odour for distances less than 100 m from the source and the stability classes E and F are not suitable for use in Gaussian models to predict agricultural odour dispersions.

Guo et al. (2003) reported that a large majority of odour events (71%) were reported during either moderately or slightly stable atmospheric conditions (stability classes E and F) during the evaluation period. They pointed out the frequency of odour occurrences has an inverse linear relationship to the wind velocity and neutral atmospheric condition with high wind speeds could also result in strong odours.

2.4 Odour Dispersion Modelling

The ultimate goal of an atmospheric dispersion model applied to odour is to accurately predict concentration downwind of any source under any atmospheric conditions (Shewchuk et al., 2006). In their comments, atmospheric processes are so complex, and our understanding so elementary, that all currently-used models have limitations on their applicability. Models have been developed to evaluate different source types (point, area, and volume), different terrain (simple or complex), different locales (urban, rural), different release rates (plume, puff) and different meteorological conditions (stable, convective) (Shewchuk et al., 2006). They suggested that the model(s) that most closely approximate the parameters of the source or characteristics of the dispersion process under analysis should be selected.

Differences between traditional dispersion modelling and odour (Diosey, 1997) modelling appear in at least three areas: at the source, at the receptor (the nose) and en-route from the source of the odours to the receptor. When conducting odour dispersion modelling, some features that agricultural odour sources are different from sources of industrial pollutants have to be taken into account. According to previous researchers (Smith, 1993; Zhu et al., 1998), these features may include (1) the odour source is at or near ground level; (2) there is insignificant plume rise due to the vertical momentum or lower density of a mass flow of warm gas; (3) the source may be of relatively large areal extent (such as an aerobic manure storages); (4) the important receptor zone may be relatively close to the source of emissions; (5) the difficulty in measuring the odour emission rate; (6) the spatial and temporal variability in emission rates; (7) the relatively low intensity of emissions. Further more, the odour concentration measurement which uses detected threshold instead of a mass concentration, which makes it critical to understand whether a normal air dispersion model can simulate odour dispersion and how to interpret the results.

2.4.1 Steady State Model

Usually, there are two types of dispersion models: steady state and non steady state. Steady state models are typically called plume models. According to Copper and Alley (2002), the basic Gaussian dispersion model equation is

$$C(x,y,z)=\frac{Q}{2\pi\delta_y\delta_z U}\exp\left[-0.5\left(\frac{y}{\delta_y}\right)^2\right]\left\{\exp\left[-0.5\left(\frac{z-H}{\delta_z}\right)^2\right]+\exp\left[-0.5\left(\frac{z+H}{\delta_z}\right)^2\right]\right\} \qquad (2.10)$$

Where: C is steady-state concentration at a specific point (g/m^3 or kg/m^3); Q is emission rate of pollutant (g/s or kg/s); σ_y and σ_z are horizontal and vertical dispersion coefficients (m); u is average wind speed at stack height (m/s); y is horizontal distances from plume centerline (m); z is vertical distance from ground level (m); H is effective stack height (m).

For ground-level concentrations ($y=z=0$),

$$C(x)=\frac{Q}{\pi\delta_y\delta_z U} \qquad (2.11)$$

A plume model assumes that the plume centerline travels in a straight line to the edge of the modeling site area regardless of whether it could physically do so at the given wind speed (Jacques Whitford Environment Ltd, 2003). For example, if the wind speed is 5 kph, the plume should travel a distance of 5 km in an hour simulation period. However, a plume dispersion model assumes that the plume will travel from the source to the edge of the modeling site, which could be 20 or 30 km. A plume model also lacks causality or memory from 1 h to the next. In other words, the direction of the plume in 1 h is unrelated to the direction of the plume during the next hour. Therefore a plume traveling in a meandering path over several hours can not be simulated. There are many steady state models commercially available for industrial air dispersion simulation and some of them such as ISCST3, and AUSPLUME have been used for odour dispersion simulation from agricultural production facilities (Keddie, 1980; Smith, 1995; Sheridan et al., 2004).

2.4.2 Non-steady state models

Non steady state dispersion models are typically called puff models. Puff models address the two disadvantages of plume models (Jacques Whitford Environment Ltd, 2003). Puff models calculate the distance that a plume can travel based on the wind speed during one simulation time period. Therefore the plume will only travel as far as the wind speed will carry it in one time period which is 5 kilometres for the above example in 3.4.1. A puff model also has memory. The position of the plume at the end of each time period becomes the starting position of the plume for the next time period as showed in Figure 3.2. In this way Puff models have a more realistic presentation of dispersion than plume models.

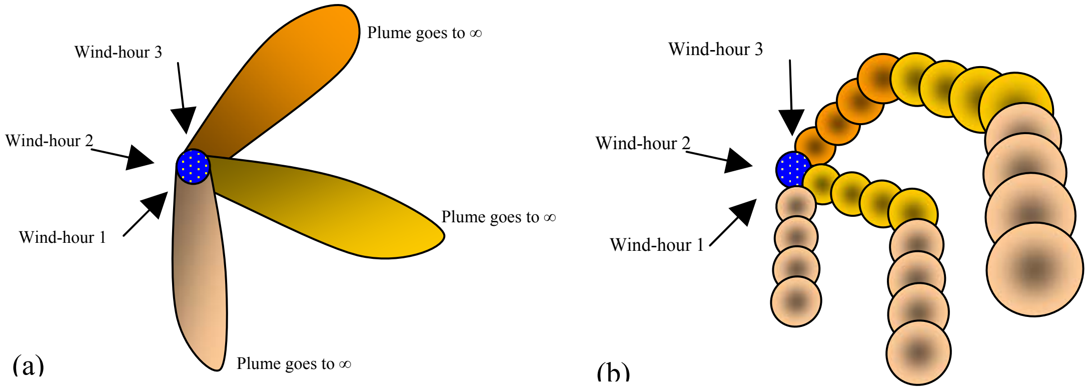


Figure 2.2 Dispersion pattern for different types of models (a) Dispersion from a Gauss steady-state model (i.e., ISCST3, and AUSPLUME) (b) Dispersion from a non-steady state models (i.e. CALPUFF, and INPUFF2) (Jacques Whitford Environment Ltd, 2003)

Mcphail (1991) suggested that puff models be used to predict agricultural odours because odour moves as a series of puffs rather than flowing as a continuous stream. CALPUFF is an example of a puff dispersion model. A Gaussian Integrated puff model INPUFF2 was developed by the USEPA and marketed by Bee-Line software Company (Asheville, N.C.). INPUFF2 has been evaluated by some researchers and proved to be suitable for use for agricultural odour dispersion, however, suitable scaling factors (35 for the barn and 10 for the manure storage) were used to adjust the modeled results to fall into the same numerical range as the field odour plume measurement data (Zhu et al., 2000; Guo et al., 2001).

2.5 Research Cap

Although the applicability of various air dispersion models to ground level odour emission from agricultural sources has been studied by some researchers, limited field data exist to evaluate their applicability in agricultural odour dispersion. With some field data obtained by University of Manitoba, University of Minnesota, and University of Saskatchewan in the last several years, it provides us enough experiment data to evaluate the air dispersion models with confidence.

3. OBJECTIVES

According to the research gap, the over-arching objective of this project was evaluation of commercial air dispersion model for livestock odour dispersion.

The first objective was to conduct sensitivity analysis and develop an understanding of how the climatic parameters affect livestock odour dispersion results for different models.

The second objective was to evaluate models with available odour plume data measured by nasal rangers (field odour assessors).

a) Three sets of odour plume measurement data were used: Nasal ranger data from University of Manitoba, University of Minnesota, and University of Saskatchewan
b) To determine the related parameters (e.g. scaling factor (or peak-to-mean ratio), conversion between odour concentration and odour intensity, etc.), and reasonable methods of adapting the selected commercial model for livestock odour dispersion simulation.

The third objective was to use the selected model to simulate odour plumes on selected typical swine farms and location(s) in Saskatchewan using historical weather data.

Chapter 4 described the first objective, sensitivity analysis. Chapter 5, 6 and 7 provided the detailed analysis for objective 2. The last objective was achieved in chapter 8. Finally, a summary and overall conclusion was included in chapter 9.

4. SENSITIVITIES OF FOUR AIR DISPERSION MODELS TO CLIMATIC PARAMETERS FOR SWINE ODOUR DISPERSION

4.1 Introduction

Changes of climatic parameters will affect the odour dispersion prediction by the models. The analysis on model's sensitivity to these climatic parameters can identify the dominant ones and their degrees of impact on downwind odour concentration and setback requirement (Smith, 1993). Smith (1993) evaluated the sensitivity of the STINK model for predicting odour concentration to various odour emission rates, wind speeds, atmospheric stability classes, ground surface roughness heights, and mean wind directions. The wind speed and odour emission rate were found the most important. Atmospheric stability and surface roughness height were shown to be the next most important parameters. Wind direction was only of moderate importance found in this study. Chastain and Wolak (1999) used a windows-based computer program, based on a simple Gaussian plume equation, to conduct similar sensitivity analysis for odour dispersion from livestock facilities. The results indicated that odour travel distances are the greatest during the stable atmospheric conditions. Neutral conditions during the day presented the next most critical period for odour dispersion. The extra vertical mixing provided by a significant increase in wind speed or the roughness associated with a forest barrier greatly reduced the distance that odour would travel. Jacques Whitford Environment Ltd. (2003) used CALPUFF (Lagrangian California Puff Model) to conduct sensitivity analyses to develop odour dispersion factors including topography, screening (windbreak or shelterbelt), and micro-climate factors to be used in the formulae for minimum separation distance calculation for Alberta, Canada. The recommended values for the topography factors were provided. The effect of vegetation screens on dispersion is very dependent on the dimensions of the screen and its location relative to the odour emission sources such as lagoons and barns. Therefore, it was not possible to develop generic values for screening. The difference between odour concentrations predicted using meteorological data for Alberta Environment Prairie and Parkland regions was insignificant and therefore it was not possible to develop generic values for micro-climate factors. In their report, they did not analyze different climate parameters effect on the agricultural odour dispersion which will be done in this study.

Individual models were evaluated for odour dispersion from livestock production sites (Smith, 1993; Zhu et al. 2000; Guo et al. 2001), however, very limited work has been done to compare various air dispersion models and identify their differences in odour dispersion predictions, which is the information that we need to help us understand the model differences and choose suitable models for odour dispersion application. Zhou et al. (2005) calibrated four air dispersion models, ISCST3 (Industrial Source Complex Short Term version 3), AUSPLUME (Australian Plume Model), INPUFF2 (Integrated PUFF version 2), and WindTrax using odour plume measurement data from two swine farms. They concluded that these four models performed similarly and predicted downwind odour concentrations with good agreement with field measured results. However, the sensitivity analysis was not conducted. Further more, in the agreements analysis, they considered odour intensity level 0, 1, 2, and 3 as the same level because of the sensitivity of the nose for these four levels. But the odour intensity level 0 means there was no odour which should be analyzed separately. CALPUFF model was compared with ISCST3 model under steady state and variable weather conditions (US EPA: Environment Protection Agency of the United States, 1998). The results showed that even though CALPUFF can be made to produce the same concentration in a steady state environment, variable meteorological conditions can produce predictions higher than that of ISCST3. An inter-comparison of the AERMOD (American Meteorological Society / Environmental Protection Agency Regulatory Model), ADMS (Atmospheric Dispersion modelling System), and ISCST3 was done to assess the AERMOD model for regulatory purposes in the UK and its performance in relation to the other advanced dispersion models (Hall et al., 2003). The comparison used four single representative boundary layer conditions, neutral (high and low wind speed), stable and unstable boundary layers, taken from a single year hourly meteorological data. AERMOD and ADMS generally showed a greater sensitivity to changes in atmospheric conditions than the ISCST3 and the maximum concentrations and their distances from the source predicted by different models were significantly different. In general, ISCST3's predictions were the most reliable while those of AERMOD were the least reliable. It was difficult to see any consistent patterns in the differences between the models as these models reacted to a multiplicity of input parameters in complex ways that were hard to distinguish. AUSPLUME, CALPUFF and TAPM (The Air Pollution Model) were evaluated and intercompared against annual dispersion data sets at Anglesea and Kwinana, Australia (Hurley, et al., 2005). AUSPLUME performed adequately for Anglesea, but performed poorly for Kwinana; CALPUFF performed marginally for Anglesea, with results worse than AUSPLUME, and performed marginally (although better than AUSPLUME) for Kwinana, with CALPUFF overpredicting extreme concentrations. TAPM performed well for both the Anglesea and Kwinana annual data sets, and outperformed both AUSPLUME and CALPUFF. The above studies indicate that these model performances were different under different simulation conditions for the industrial air pollutant dispersion.

In summary, very limited research has been conducted on comparing various industrial air dispersion models' predictions for agricultural odours and the sensitivities of these models to various climatic parameters. The objectives of this study were to a) conduct sensitivity analysis of four commonly used air dispersion models, i.e. ISCST3, AUSPLUME, CALPUFF, and INPUFF2, as affected by the primary climatic parameters and b) compare the predictions of these models under various climatic conditions.

4.2 Materials and Methods

4.2.1 Model Descriptions

Four air dispersion models were used in this study, i.e. ISCST3, AUSPLUME, CALPUFF and INPUFF2. ISCST3, AUSPLUME and CALPUFF are all US EPA's regulatory models. INPUFF2 has been evaluated as a proper model to predict the livestock odour dispersion (Zhu et al., 2000; Guo et al., 2001; Zhou et al., 2005).

4.2.1.1 ISCST3

ISCST3 (Industrial Source Complex) model is designed to support the US EPA's regulatory modeling programs and is widely used in North America and worldwide (US EPA, 1995). It is a steady-state Gaussian plume dispersion model. The model can handle multiple sources, including point, volume, area, line and open pit sources. Source emission rates can be treated as constant throughout the modeling period, or may be varied by month, season, hour of a day, or other optional periods. The user can specify multiple receptor networks in a single run, and may also mix Cartesian grid receptor networks and polar grid receptor networks in the same run. It runs with a sequence of hourly meteorological conditions to predict hourly average concentrations at receptors. Topography can be taken into account only when the deposition is considered.

4.2.1.2 AUSPLUME

AUSPLUME model was developed by Australian Environmental Protection Authority and it is an extension of the ISCST3 model (Australian EPA, 2000). It is designed to predict ground-level concentrations or dry deposition of pollutants emitted from one or more sources, which may be stacks, area sources, volume sources, or any combination of these. Up to 101×101 gridded receptors can be handled in one run. The discrete receptors can be run with gridded receptors at the same time. AUSPLUME allows the calculation of average concentrations to be minimum averaging time of three minutes even though the meteorological data are hourly. It may take account of the topography by adjusting ground roughness height (Smith, 1972). The output data file contains gridded concentration fields for each source group and for each averaging period.

4.2.1.3 CALPUFF

CALPUFF air dispersion model was an US EPA regulatory model based on Lagrangian puff model designed to simulate continuous puffs of pollutants being emitted from a source into the ambient wind flow (US EPA, 1995, and US EPA, 1998). It consists of three sub-systems: CALMET, CALPUFF, and CALPOST. CALMET is a meteorological model that combines meteorological data and geophysical data to generate a wind field. The CALPUFF model then combines the information provided by CALMET and source data to predict concentration, deposition flux, visibility impairment, etc., at each receptor for specified averaging time. CALPOST is a post-processor for the model. CALPUFF was recently elevated to USEPA preferred model status. It has the strengths on contemplating appropriate source types and averaging periods and handling building downwash and complex terrain.

CALPUFF can accommodate point, volume, and area source emissions. Up to 50×50 gridded receptors and discrete receptors can be handled in one run time. CALPUFF can use the three dimensional meteorological fields developed by the CALMET model or the meteorological files used by the ISCST3. CALPUFF contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, sub-grid scale terrain interactions as well as long range effects such as pollutant removal, chemical transformation, vertical wind shear, over water transport, and coastal interaction effects. Most of the algorithms contain options to treat the physical processes at different levels of details depending on the model application. Topography can be incorporated into the simulation.

4.2.1.4 INPUFF2

INPUFF2, a Gaussian integrated puff model, was developed by the US EPA and marketed by Bee-Line software Company (Asheville, N.C.). The Gaussian puff diffusion method is used to compute the contribution to the concentration at each receptor from each puff every time step. It can simulate dispersion of airborne pollutants from semi-instantaneous or continuous point sources. There is no treatment of area or volume sources. It may deal with non-reactive pollutants, deposition, and sedimentation. One-hundred gridded receptors can be used and the number of discrete receptors is up to 1999. A maximum of 144 separate meteorological periods of the same length may be used during each run. It can deal with different time intervals with minimum of 1 s instead of 1 h required by the other models. This makes it suitable for simulating odours as measured by field odour assessors. This model has some consideration of terrain effects through the wind field but there is no explicit treatment of complex terrain.

4.2.1.5 Required Model Setup Data

Generally, the model setup data include source information, meteorological file, receptor layout, dispersion parameters and the output file. Firstly, source location and type (point, area, and volume) needed to be determined and then the emission rate can be input for the corresponding source. Secondly, the meteorological data could be prepared. The minimum amount of data required is a list of hourly values (preferably hourly averages) of wind speed, wind direction, ambient temperature, atmospheric stability (Pasquil class) and mixing depth. The receptor layouts include gridded receptors and discrete receptors depending on different simulations. The model dispersion parameters usually include the use of stack-tip downwash, buoyancy-induced dispersion, final plume rise (except for sources with building downwash), a routine for processing averages when calm winds occur, default values for wind profile exponents and for the vertical potential temperature gradients, and the use of upper bound estimates for super-squat buildings having an influence on the lateral dispersion of the plume. The default mode of operation for the models can be selected for the odour dispersion. Finally, the output file needs to be specified. Concentration output is normal. The frequency output is another option. In the output options, we can produce the output plot file so that we can make a contour map. Figure 4.1 showed the model flow chart.

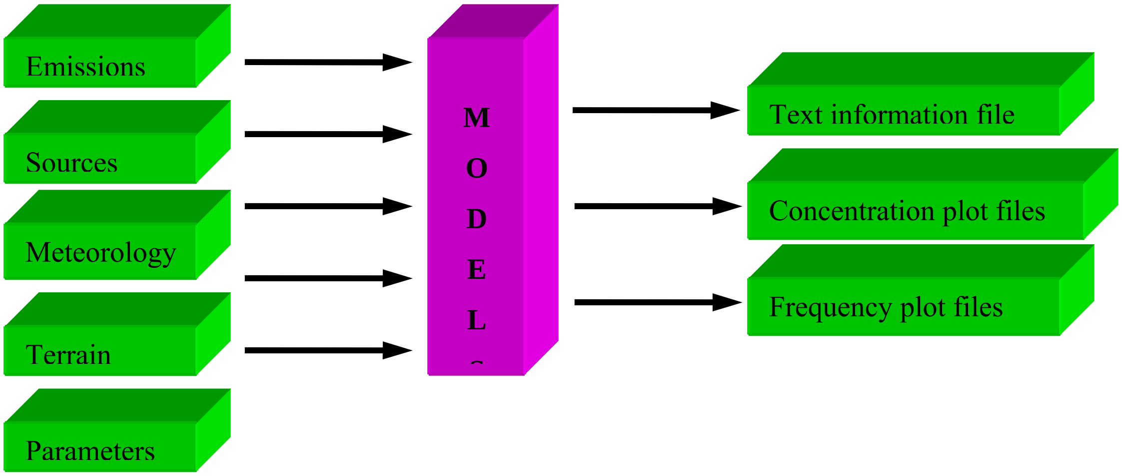


Figure 4.1 Model information flow (EPA, 2000)

4.2.2 Swine Farm

The swine farm was located in eastern Saskatchewan, Canada (Figure 4.2). It consisted of one barn with 10 rooms for 11,550 head feeder pigs and an uncovered two-cell earthen manure storage basin. The barn was mechanically ventilated with wall-mounted fans. There were shallow manure pits underneath the fully slatted floor that were gravity-drained once every 2 to 4 weeks. The odour emission rates used in this study are given in Table 4.1

The study area was a rural crop field with flat terrain and free of obstacles. The prevailing winds are from West-North-West (WNW). This direction is used for simulating odour dispersion from the farm.

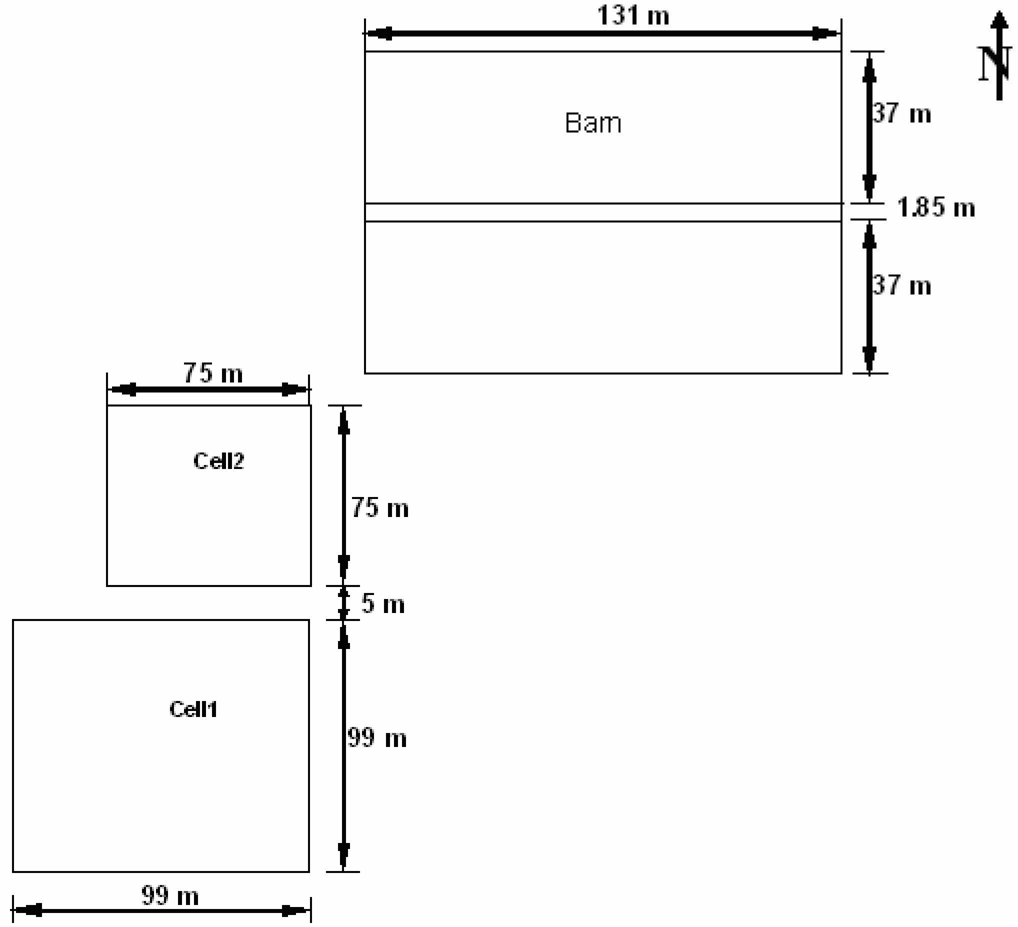


Figure 4.2 Layout of the swine farm

Table 4.1 Odour emission rates from the barn and manure storages

Source	Total emission rate (OU/s)	Odour emission rate (OU m^{-2} s^{-1})
Barn	437,928	44.9
Cell 1	270,537	48.1
Cell 2	325,944	33.3

4.2.3 Model climatic sensitivity analysis

Two types of meteorological conditions were considered. One is steady state meteorological conditions so as to evaluate the sensitivities of the models as affected by each meteorological parameter under steady state meteorological conditions and to reveal the true prediction differences of the four models without the bias of a varying meteorological regime (US EPA, 1998). The influence of mixing height, ambient temperature, atmospheric stability, wind speed, wind direction under steady state weather condition on the model predictions could then be determined. Another is the variable meteorological condition using 2003 annual hourly meteorological data in this study area in order to obtain the annual average odour concentrations in the study area, therefore, odour concentration predictions under variable meteorological conditions could be compared with that under steady state meteorological conditions.

The odour transportation distances predicted by the four models under various weather conditions were compared. The maximum odour travel distance was defined as the maximum distance from the source where odour concentration is reduced to 10 OU/m^3. Because the distance of interest for setback determination is within 5 km from the source (Guo et al. 2004), the odour concentrations predicted by the models were also compared within 5 km from the swine farm.

4.2.4 Weather conditions

For steady state meteorological conditions, seven weather conditions from the stable weather F1 to unstable weather C5 that favour odour travel and result in high odour concentrations at the ground level downwind of the odour sources are chosen for this study, i.e.:

- F1: Atmospheric stability F (moderately stable) with wind speed 1 m/s,
- F3: Atmospheric stability F (moderately stable) with wind speed 3 m/s,
- E3: Atmospheric stability E (slightly stable) with wind speed 3 m/s,
- E5: Atmospheric stability E (slightly stable) with wind speed 5 m/s,
- D5: Atmospheric stability D (neutral) with wind speed 5 m/s,
- D8: Atmospheric stability D (neutral) with wind speed 8 m/s, and
- C5: Atmospheric stability C (slightly unstable) with wind speed 5 m/s.

Under the other weather conditions that are less stable than C5, strong vertical mixing will result in great air dispersion and normally would not allow odour to travel for long distance.

4.2.5 Computation Assumptions

The following assumptions apply to odour dispersion simulation under the steady state meteorological conditions:

1. All odour sources were considered as point sources in INPUFF2 simulation; for the other three models, the barn was considered as point sources and the two manure storage cells were considered as area sources. For all models, the barn was separated into 32 point sources to best represent the shape of the barn. The odour emitting height was 1.5 m for the barn and 0 m on ground level for the manure storage cells.

2. The odour emission rates from the barn and the manure storage cells were constant as given in Table 1 in order to exclude the effects of changing source emission on the odour dispersions.
3. For the barn, the exhaust air temperature was assumed as 16°C when ambient temperature was from -30 to 16°C while it was 2°C above the ambient temperature when the ambient temperature was higher than 16°C. The manure storage cells' odour exit temperature was considered the same as the ambient air temperature.
4. Due to the fact that the barn area was considered as point source instead of individual fans, the odour exit velocity was considered as 0.05 m/s. Odour exit velocities from the manure storage cells were also considered as 0.05 m/s.
5. The model simulation time was set up to allow the odour travel the farthest distance before the centerline odour concentration reduced to 10 OU/m^3.
6. The receptor's detection height was considered as 1.5 m above the ground because the field odour sniffers' nose height is approximately 1.5 m.
7. Wind speed and direction were both horizontally homogeneous in the study area.
8. The wind direction was from WNW, except for the studies with various wind directions.
9. During all the simulations, deposition or chemical transformation were not considered.

When simulating odour dispersion using hourly annual weather data, the same assumptions were applied except 3, 5, and 8. The barn odour emitting temperature and the manure storage odour emitting temperature are constant at 16°C. Receptors were arranged in grid format of 100 m from each other within 3 km from the farm.

4.3 Results and Discussion

4.3.1 Mixing Height

Mixing height is defined as the depth of the surface boundary layer in which thermally-generated or shear-generated turbulence is found. Under all the seven weather conditions F1 to C5 and ambient temperature of 20°C, the simulation results indicated that the mixing height had no effect on the model predictions for all models when mixing height was between 50 and 3000 m. However, predictions from different models were different, as found with the other meteorological parameters later.

4.3.2 Ambient Temperature

The effects on odour dispersion of ambient temperature from -20 to 30^{o}C were evaluated under steady state weather conditions of E3 and D5, with a mixing height of 1500 m.

4.3.2.1 Effect on maximum odour travel distance

Figure 4.3 shows the odour travel distance under F3, E3 and D5. The odour travel distance increased with the increase of ambient temperature. With the simulation condition F3, when the increase of the ambient temperature from -20 to 30 ^{o}C, the maximum dispersion distance where the odour concentration reached 10 OU/m^{3} increased 9.8, 15.2, 9.7, and 52.5% as predicted ISCST3, AUSPLUME and CALPUFF, and INPUFF2 models, respectively. Under E3, the maximum distance increased 9.9, 14.8, 8.7, and 47.6% as predicted by the four models, respectively; while the increase under D5 were, 8.1, 8.6, 4.2, and 34.6%, respectively. Hence, the more unstable the weather condition, the less effect of ambient temperature had on odour dispersion. The ambient temperature has much greater effect on INPUFF2 than on the other models. CALPUFF is the least sensitive to ambient temperature.

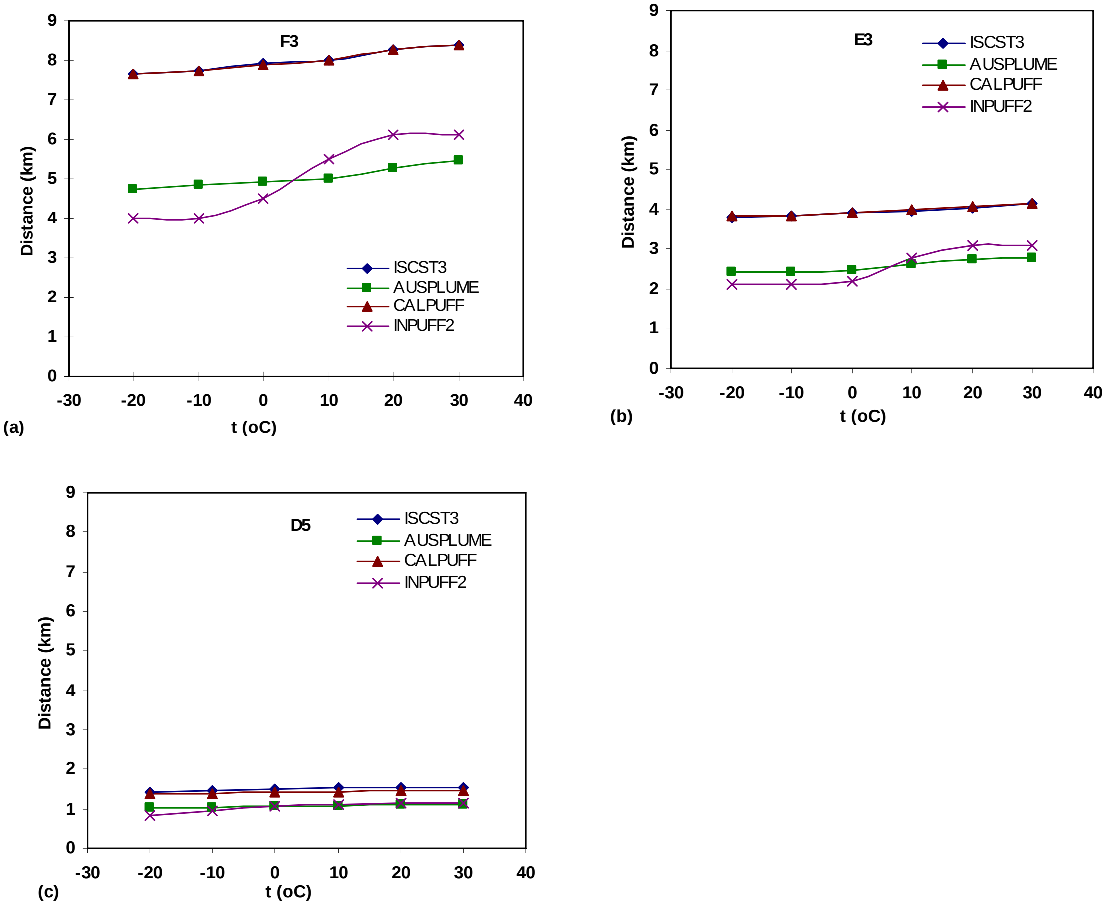


Figure 4.3 Effect of Ambient Temperature on Odour Travel distances under (a) F3: Stability F with wind Speed 3 m/s; (b) E3: Stability E with Wind Speed 3 m/s and (c) D5: Stability D with wind Speed 5 m/s

Table 4.2 summarizes the differences of the predicted odour travel distances by the other three models compared to ISCST3. The difference, in %, was calculated by the following equation:

$$Difference(\%) = \frac{X_{Model} - X_{ISCST3}}{X_{ISCST3}} \times 100 \tag{4.1}$$

where X_{Model} and X_{ISCST3} are the model predicted maximum distances, km.

ISCST3 almost always predicted the greatest odour travel distances followed by CALPUFF, which had predictions very close to that of ISCST3 under F3 and E3 but lower under D5. AUSPLUME’s predictions were higher than that of INPUFF2 when temperature was below 0^{o}C but lower when temperature was above 0^{o}C. Comparing the differences between E3 and D5, the model differences were greater under stable weather conditions than neutral weather conditions while opposite for CALPUFF.

Table 4.2 Difference (%) on odour travel distances between the other models and ISCST3

Weather conditions	Temperature(C°)	Difference with ISCST3 (%)		
		AUSPLUME	CALPUFF	INPUFF2
F3	-20	-37.9	0.0	-47.6
	-10	-37.6	0.0	-48.4
	0	-37.7	-0.1	-43.1
	10	-37.4	-0.2	-31.4
	20	-36.2	-0.1	-26.3
	30	-34.8	0.0	-27.2
E3	-20	-36.2	1.1	-44.5
	-10	-37.1	-0.2	-45.3
	0	-37.0	-0.2	-43.6
	10	-33.3	1.1	-29.6
	20	-31.9	1.1	-22.7
	30	-33.4	0.0	-25.5
D5	-20	-28.1	-3.2	-41.1
	-10	-29.9	-5.6	-34.4
	0	-28.7	-5.5	-29.1
	10	-29.4	-5.9	-26.2
	20	-27.3	-6.1	-26.5
	30	-27.7	-6.6	-26.7

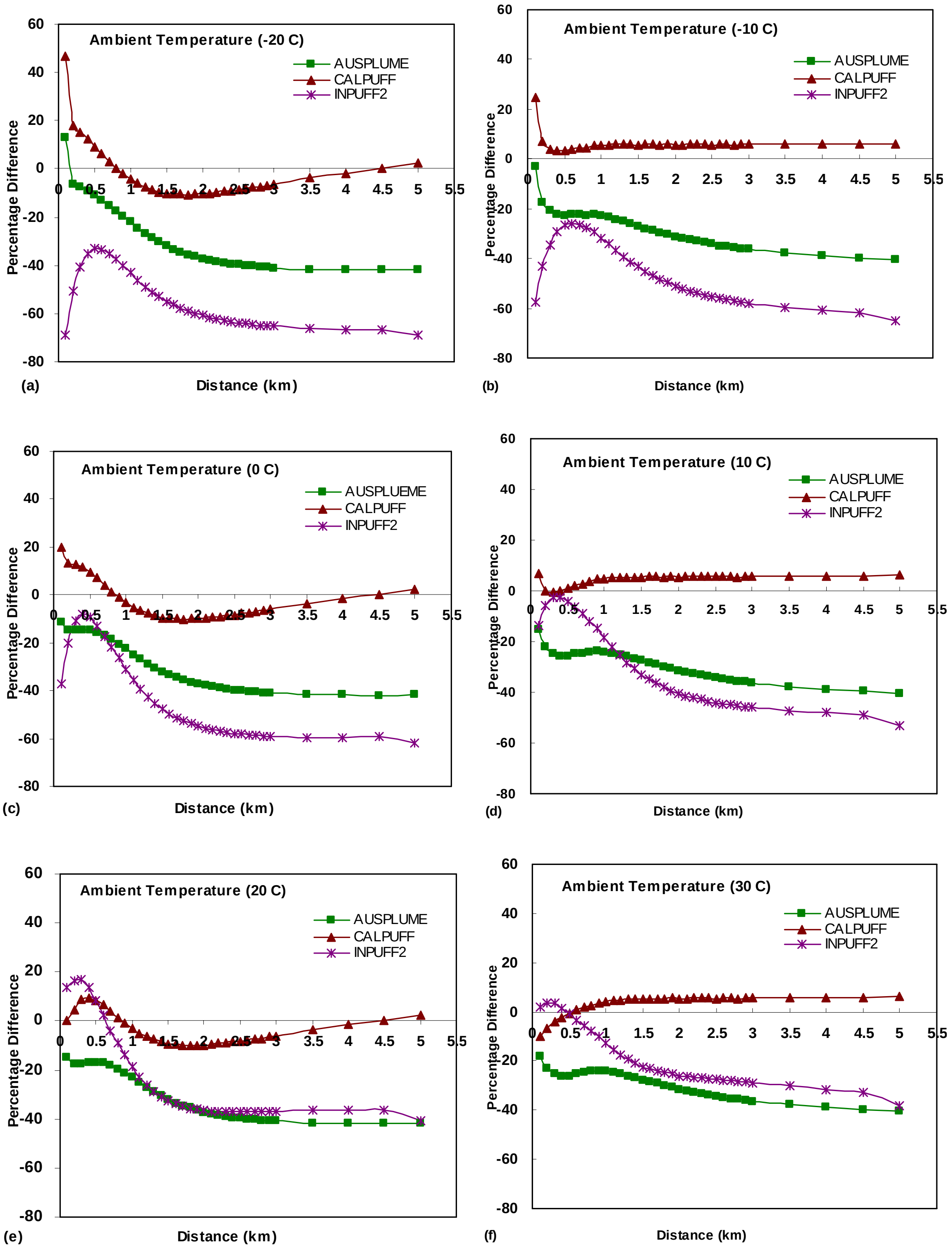
4.3.2.2 Odour concentration within 5 km

The receptors were placed along 72 direction radials, beginning with 0^o (North) and incrementing by 5^o clockwise. In each direction, thirty-three receptors were placed from the source on the centerline of the odour plume with distance of 100 m from each other within 3 km and 4 receptors every 500 m from 3 to 5 km. The predicted odour concentrations under D5 on the plume centerline were given in Table 4.3. The odour concentration decreased with the increase of the downwind distance. At the same distance, the odour concentration increased when the ambient temperature increased. At 500 m, the differences ranged from 38% (AUSPLUME) to 123% (INPUFF2). At 1 km, the differences began to disappear except for INPUFF2 (66%). These results agreed with the field measurement result that the higher the temperature, the stronger the odour was (Pan et al., 2005).

Table 4.3 Plume centerline odour concentration at various distances downwind under D

Distance (km)		1	1.5	2	2.5	3	3.5	4	4.5	5
ISCST3	-20	13	10	7	6	5	4	3	3	2
	-10	12	8	6	5	4	3	3	2	2
	0	14	10	8	6	5	4	3	3	2
	10	13	9	7	5	4	3	3	2	2
	20	14	10	8	6	5	4	3	3	2
	30	13	9	7	5	4	3	3	2	2
AUSPLUME	-20	10	7	5	3	3	2	2	2	1
	-10	9	6	4	3	3	2	2	1	1
	0	11	7	5	4	3	2	2	2	1
	10	10	6	4	3	3	2	2	2	1
	20	11	7	5	4	3	2	2	2	1
	30	10	6	4	3	3	2	2	2	1
CALPUFF	-20	12	9	7	5	4	4	3	3	2
	-10	13	9	7	5	4	4	3	3	2
	0	13	9	7	5	4	4	3	3	2
	10	14	9	7	5	4	4	3	3	2
	20	14	9	7	5	4	4	3	3	2
	30	14	9	7	5	4	4	3	3	2
INPUFF2	-20	7	4	3	2	2	1	1	1	1
	-10	8	5	3	2	2	1	1	1	1
	0	9	5	3	2	2	2	1	1	1
	10	11	6	4	3	2	2	2	1	1
	20	12	7	5	4	3	2	2	2	1
	30	12	7	5	4	3	2	2	2	1

ISCST3 was also used as the basic model to compare the models' differences in odour concentration predictions and similar results were obtained as model differences for the maximum odour travel distances. As illustrated in Figure 4.4, CALPUFF's predictions were 10% lower than that of ISCST3 beyond 1 km while AUSPLUME and INPUFF2's predictions were lower than that of ISCST3 by up to 70% except at very close distance under low temperatures.


(a) Ambient Temperature (-20 C)

(b) Ambient Temperature (-10 C)

(c) Ambient Temperature (0 C)

(d) Ambient Temperature (10 C)

(e) Ambient Temperature (20 C)

(f) Ambient Temperature (30 C)

Figure 4.4 Odour Concentration Differences between Model Predictions Comparing with ISCST3 under Different Ambient Temperatures

4.3.3 Atmospheric Stability

4.3.3.1 Impact on Maximum Odour Travel Distance

The effect of atmospheric stability on the distance of odour dispersion is shown in Figure 4.5 under ambient temperature of 20°C and mixing height of 1500 m. The results indicate that as the atmospheric stability changed from stable (F1) to unstable (C5), the odour travel distance decreased rapidly by 95% to 97%. Hence, atmospheric stability had significant effect on odour dispersion and these four models had similar sensitivity to the atmospheric stability. This is consistent with the finding of Chastain and Wolak (1999). It is also consistent with the result reported by Guo et al. (2003) that the majority of odour events were reported during either moderately or slightly stable atmospheric conditions. It is important to point out that the great odour travel distances obtained with F1 and F3 were under the hypothetical assumption that the weather condition would remain steady for long enough time to allow odour to travel to such distances, i.e. 5 to 6 h with F1 or 2 h with F3. In reality, it is extremely rare that such weather conditions would occur without any wind direction shift.

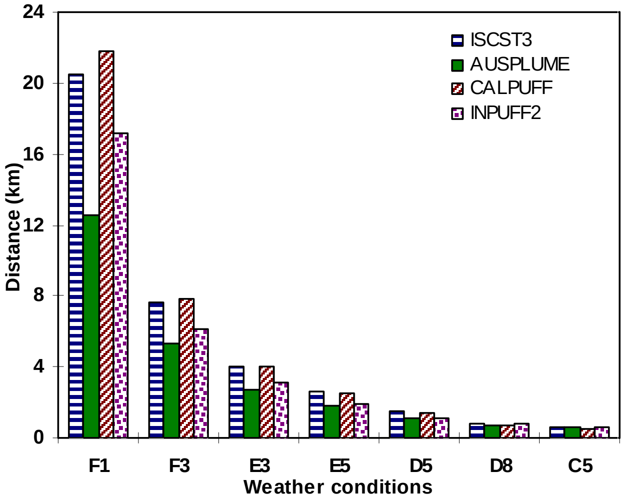


Figure 4.5 Effect of atmospheric stability on odour travel distances

Table 4.4 shows the differences in maximum odour travel distances of the other models comparing to that of ISCST3. AUSPLUME predicted the lowest values under F1 to D8, which was 11.5 to 38.9% lower than that of ISCST3, followed by INPUFF2 that was 2.2 to 27.8% lower than ISCST3; while under C5 AUSPLUME's prediction was higher than INPUFF2. CALPUFF's predictions were close to ISCST3 with -11.5 to 6.1% of difference except under C5. The differences between AUSPLUME or INPUFF2 and ISCST3 decreased as the instability of the weather increased and were only -11.5 to 0% under D8 and C5.

Table 4.4 Summary of differences (%) on odour travel distance between the other models and ISCST3

Weather conditions	Difference with ISCST3 (%)		
	AUSPLUME	CALPUFF	INPUFF2
F1	-38.9	6.1	-16.2
F3	-30.7	2.8	-19.9
E3	-31.9	1.1	-22.7
E5	-31.6	-2.6	-27.8
D5	-27.3	-6.1	-26.5
D8	-11.5	-11.5	-3.1
C5	0.0	-17.0	-2.2

4.3.3.2 Odour concentration within 5 km

Modeled odour plume centerline concentrations within 5 km downwind are given in Table 4.5. Although odour concentrations are high under stable weather conditions F1 to E5 at 100 m from the farm, this distance is usually within the property line of the swine farm, therefore, is not of interest to the neighbouring community. Furthermore, the air dispersion models are not designed to predict odour concentrations at such close distance. At 500 m, although the predicted odour concentrations were high ranging from 82 to 419 OU under F1, this weather condition seldom occurs. For F3, odour concentration ranged from 51 to 140 OU at 500 m, gradually reduces with the increase of distance, and at 3 km, i.e. the maximum setback distance required by the setback guideline of the Canadian Prairie Provinces, is 27 OU or lower. Under E3 to C5, odour concentration at 3 km is 1 to 13 OU. The odour plume centerline concentration at 3 km reduced 98 to 99% when weather changed from F1 to C5.

Table 4.5 Downwind odour concentration under weather conditions F1 to C5

Distance (km)		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
F1	ISCST3	82	100	94	98	67	80	52	61	43	46
	AUSPLUME	102	114	79	82	55	56	41	40	32	30
	CALPUFF	397	213	142	105	85	72	62	55	50	45
	INPUFF2	419	211	130	90	70	57	49	44	39	36
F3	ISCST3	51	42	47	35	27	27	20	21	16	16
	AUSPLUME	54	45	30	29	20	19	14	14	11	10
	CALPUFF	138	72	47	35	29	24	21	19	17	15
	INPUFF2	140	70	43	30	23	19	16	15	13	12
E3	ISCST3	42	32	25	21	15	14	11	10	8	7
	AUSPLUME	42	28	18	15	10	9	7	6	1	5
	CALPUFF	79	39	26	20	16	13	11	10	8	7
	INPUFF2	80	34	21	15	12	10	9	8	7	6
E5	ISCST3	29	20	14	13	9	9	6	6	5	4
	AUSPLUME	28	17	11	9	6	5	4	4	3	3
	CALPUFF	48	23	16	12	9	8	7	6	5	4
	INPUFF2	48	21	13	9	7	6	5	5	4	4
D5	ISCST3	27	14	9	8	5	5	3	3	2	2
	AUSPLUME	22	11	6	5	3	3	2	2	2	1
	CALPUFF	29	14	9	7	5	4	4	3	3	2
	INPUFF2	29	12	7	5	4	3	2	2	2	1
D8	ISCST3	17	9	6	5	3	3	2	2	2	1
	AUSPLUME	14	7	4	3	2	2	1	1	1	1
	CALPUFF	18	9	6	4	3	3	2	2	2	1
	INPUFF2	18	7	4	3	2	2	2	1	1	1
C5	ISCST3	13	6	3	2	2	1	1	1	1	1
	AUSPLUME	10	4	2	1	1	1	1	0	1	0
	CALPUFF	14	6	4	2	2	1	1	1	1	1
	INPUFF2	12	5	3	2	1	1	1	1	1	0

The differences between the other models' and ISCST3 on of odour concentration predictions were also analyzed for F1 and C5, which was great within 1 km but very small at 2 to 5 km. Under stable weather conditions F1, the difference was as high as 5440% for INPUFF2 and 4845% for CALPUFF at 100 m. At the same distance but under F3, the difference decreased but still high with 1839% for CALPUFF and 1640% for INPUFF2. For AUSPLUME, the difference was relative low with 57% for F1 and 45% for F3. When the weather conditions changed to neutral to unstable under D8 and C5, the differences between the models' predictions were very limited, as indicated in Figure 4.6.

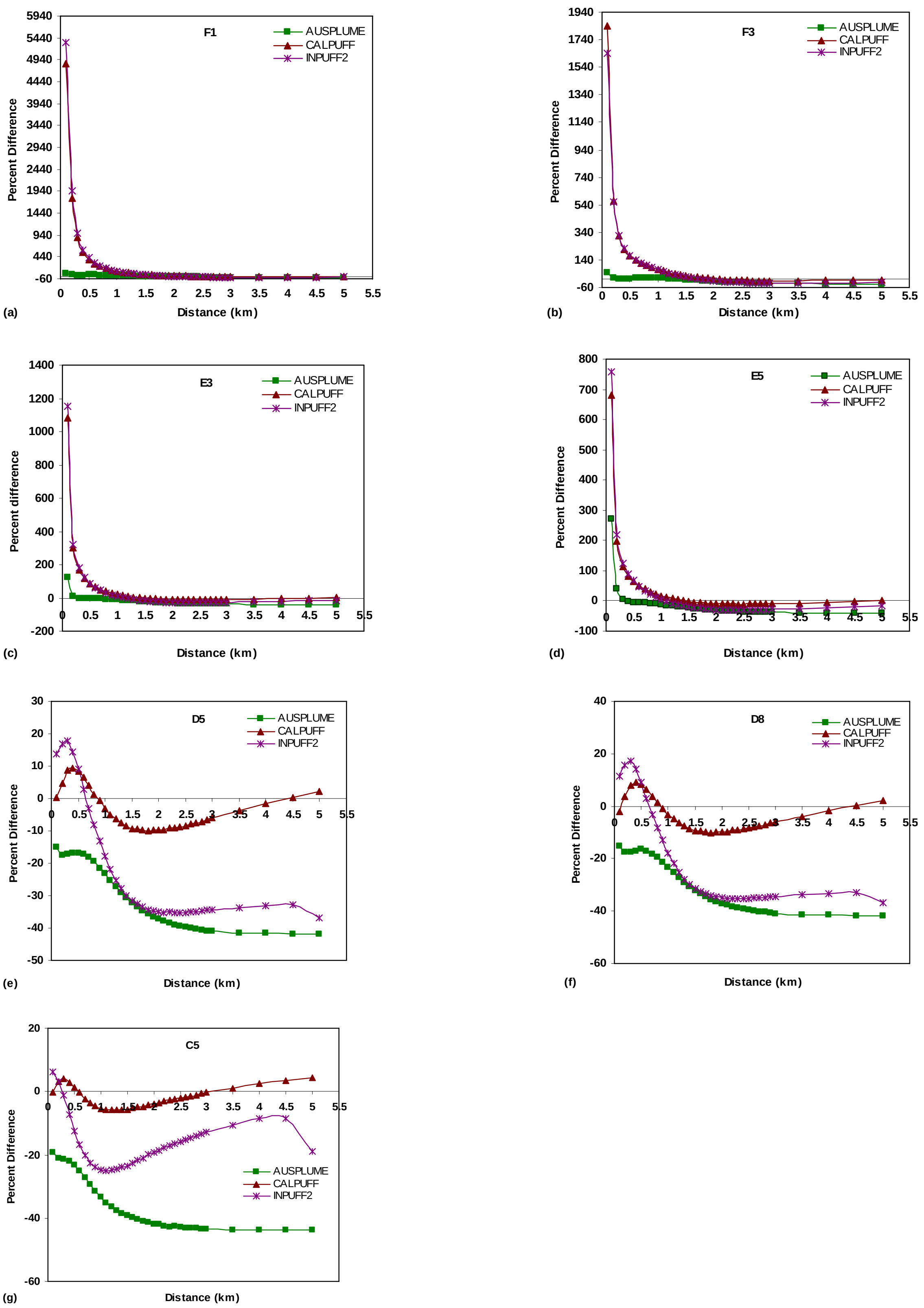


Figure 4.6 Odour concentration differences between model predictions comparing with ISCST3 under different atmospheric stabilities

4.3.4 Wind Speed

4.3.4.1 Maximum Dispersion Distance Analysis

The influence of wind speed on odour dispersion was shown in Figure 4.7 under slightly stable atmospheric stability class E and neutral stability class D, with ambient temperature of 20 °C and mixing height of 1500 m. As wind speed increased, the maximum distance to achieve 10 OU/m^3 decreased. Similar result was obtained by Chastain and Wolak (1999). Under stability class E, when the wind speed increased from 1 to 5 m/s, the maximum distances decreased by 73%, 70%, 70%, and 79% for ISCST3, AUSPLUME, CALPUFF, and INPUFF2, respectively. Wind speed has more impact on INPUFF2 and ISCST3 than AUSPLUME and CALPUFF under stability class E. Under stability class D, when the wind speed increased from 3 to 8 m/s, the maximum distance decreased by 67%, 56%, 68%, and 54% for ISCST3, AUSPLUME, CALPUFF, and INPUFF2, respectively. ISCST3 and CALPUFF are more sensitive to wind speed than AUSPLUME and INPUFF2 under stability class D. Wind speed has more impact on maximum distance with stable weather than neutral weather. The increased turbulence associated with high wind speeds enhances air mixing, therefore, decreases the horizontal odour dispersion.

Comparing the four models, AUSPLUME always predicted the lowest distances that were 11.5 to 38.4% lower than that of ISCST3; INPUFF2's predictions were 3.1 to 31.5% lower than that of ISCST3; and CALPUFF's predictions were within -14.8 to 1.1% of that of ISCST3. The higher the wind speed, the lower the differences between the models were.

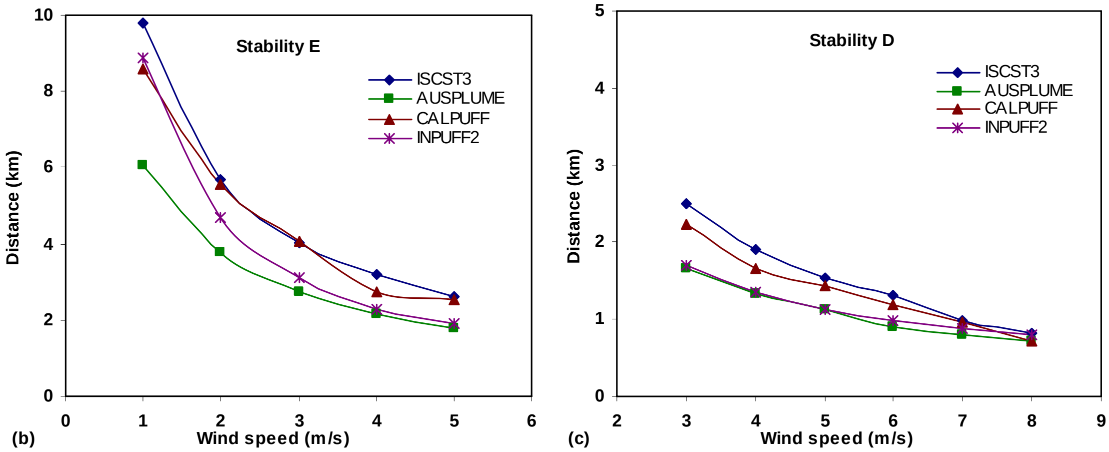


Figure 4.7 Effect of wind speed on odour dispersion

4.3.4.2 Odour Concentration Analysis within 5 km

Within 5 km, the odour concentration decreases with the increase of wind speed (Table 4.6). These results are consistent with the observations by Guo et al. (2003) that there were high occurrences of odour events during periods of low wind speeds. Pan et al. (2005) also concluded that under a high wind speed odour level decreases faster comparing with low wind speed. Comparing the four models, AUSPLUME always predicted the lowest odour levels that were up to 40% lower than that of ISCST3, as showed in Table 4.6. Within 0.5 km, CALPUFF predicted higher odour concentration comparing to that of ISCST3 but was lower than that of ISCST3 beyond 0.5 km by up to 8%. INPUFF2 gives higher values than ISCST3 within 0.5 km but lower beyond 0.5 km by up to 40%.

Table 4.6 Odour concentrations downwind with different wind speed under SC D

Model	Wind speed (m/s)	Distance (km)									
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
ISCST3	3	45	24	17	13	10	8	6	5	4	4
	5	27	14	10	8	6	5	4	3	3	2
	8	17	9	6	5	4	3	2	2	2	1
AUSPLUME	3	37	18	12	8	6	5	4	3	3	2
	5	22	11	7	5	4	3	2	2	2	1
	8	14	7	4	3	2	2	1	1	1	1
CALPUFF	3	49	23	15	12	9	7	6	5	4	4
	5	29	14	9	7	5	4	4	3	3	2
	8	18	9	6	4	3	3	2	2	2	1
INPUFF2	3	48	19	11	8	6	5	4	3	3	2
	5	29	12	7	5	4	3	2	2	2	1
	8	18	7	4	3	2	2	2	1	1	1

4.3.5 Wind Direction

4.3.5.1 Maximum Dispersion Distance Analysis

Wind directions from west north-west (WNW), west (W), south-west (SW), and south (S) were selected to simulate the odour dispersion from the swine farm under E3 and D5. The ambient temperature is 20^{o}C and mixing height is 1500 m.

Under E3, the maximum distance for 10 OU/m^3 changed greatly with various wind directions as simulated by INPUFF2 (Figure 4.8) which increased by 51.9% from 2.7 km with S wind to 4.1 km with SW wind. The wind directions had limited effect on the other models with the maximum effect on ISCST3 from 3.5 km with S wind to 4.2 km with W wind, a 20% increase. However, under D5, wind direction had significant effect on all models except AUSPLUME. The maximum distances occurred with SW wind for CALPUFF and W for ISCST3, and the minimum distances occurred with S wind for the three models except AUSPLUME. CALPUFF had the largest difference between the odour travel distances under S and SW winds with 0.85 and 1.8 km, respectively, increased by 112%. Hence, odour source orientations affect downwind odour concentration. With the SW wind, the three odour sources were in a line resulting in the highest odour concentration downwind; while with S wind the barn was parallel with the EMSs so the centerlines of the plumes of the barn and EMSs were separated that resulted in the lower downwind odour concentrations. The differences among these four models were significant, e.g. CALPUFF predicted an odour travel distance of 1.8 km with SW wind while that of AUSPLUME was 1.2 km.

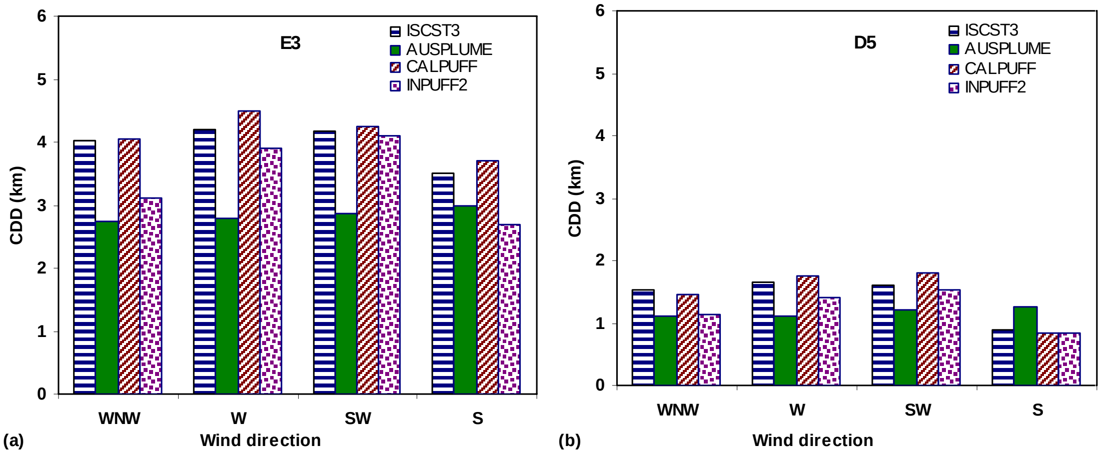


Figure 4.8 Effect of wind direction on odour dispersion

4.3.5.2 Odour Concentration Analysis within 5 km

Table 4.7 gives the modeled odour concentrations within 5 km under D5. The closer to the source, the more significant the wind direction effect is on the odour concentration. S wind was used as the basic wind direction to compare the wind directions' impact. At close distance from the source, the impact of wind direction is significant for all models, the maximum differences between the odour concentrations of the four directions at distances of 0.1, 0.5, 1, and 2 km were 195% (ISCST3), 135% (CALPUFF), 104% (CALPUFF), and 40% (CALPUFF); the differences reduced to the minimum of 1% to maximum of 27%, 16%, and 11% (INPUFF2) at 3, 4, and 5 km. The results showed that the source orient has significant effect on the odour dispersion, especially at closer distance to the source.

Table 4.7 Odour concentration with different wind directions

Distance(km)		0.1	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
ISCST3	S	38	15	9	7	6	5	4	3	3	3	2
	SW	37	24	16	11	8	6	5	4	3	3	2
	W	88	33	17	11	8	6	5	4	3	3	2
	WNW	112	27	14	10	8	6	5	4	3	3	2
AUSPLUME	S	62	45	17	9	6	4	3	2	2	2	1
	SW	15	38	16	9	6	4	3	2	2	2	1
	W	40	13	8	6	5	3	3	2	2	2	1
	WNW	96	22	11	7	5	4	3	2	2	2	1
CALPUFF	S	47	15	9	7	6	5	4	4	3	3	2
	SW	26	23	16	11	8	6	5	4	3	3	3
	W	92	35	18	12	9	6	5	4	3	3	3
	WNW	113	29	14	9	7	5	4	4	3	3	2
INPUFF2	S	44	16	9	6	5	4	3	2	2	2	2
	SW	32	24	15	10	7	5	4	3	2	2	2
	W	68	27	14	9	6	5	4	3	2	2	2
	WNW	128	29	12	7	5	4	3	2	2	2	1

The differences on odour concentration predictions between the models comparing with ISCST3 are showed in Figure 4.9. CALPUFF's predictions for odour concentrations were similar with that of ISCST3 for all wind directions. INPUFF2's results were similar to that of ISCST3 for S and SW winds but mostly lower with W and WNW winds. The odour concentrations predicted by AUSPLUME were higher than that of ISCST3 at close distances but lower at long distances for S and SW winds while always lower than that of ISCST3 for W and WNW winds.

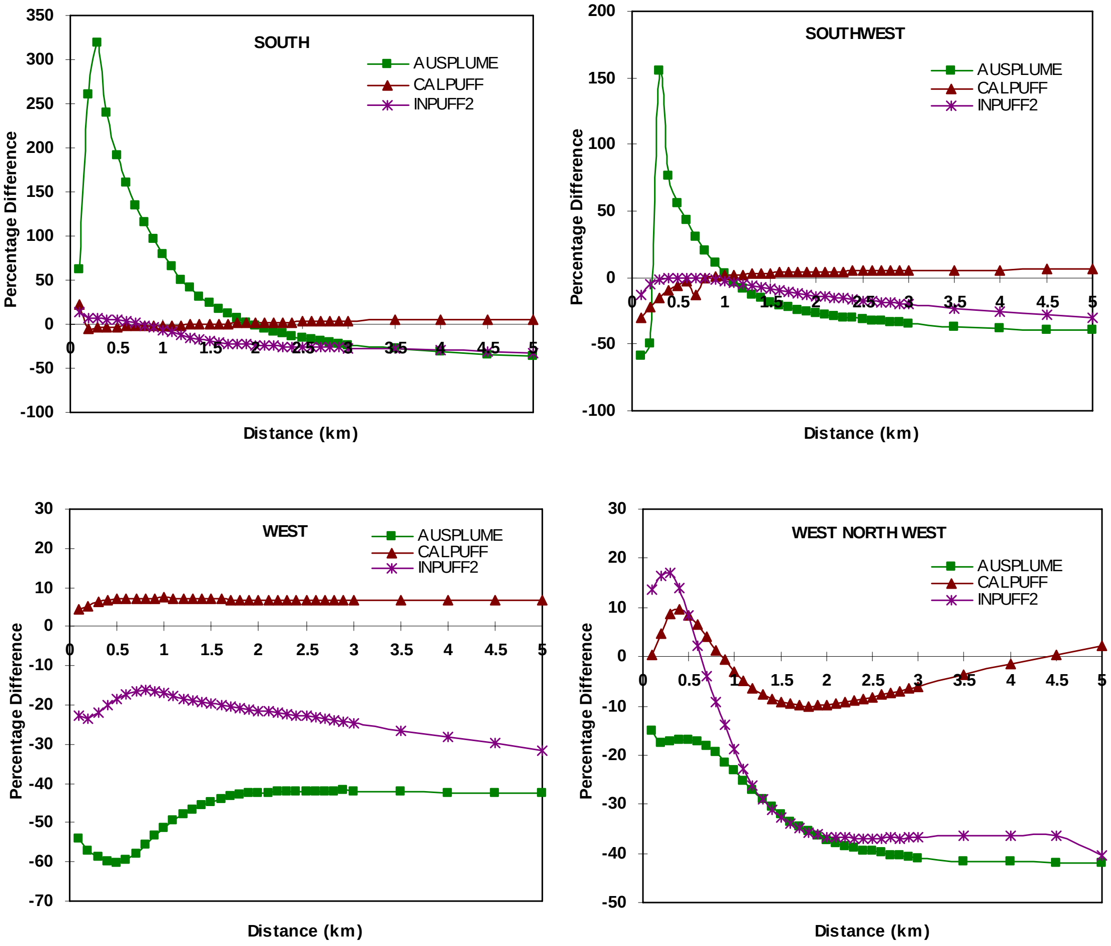


Figure 4.9 Differences of the models with ISCST3 for odour concentration with different wind directions

4.3.6 Variable meteorological conditions

To obtain the annual average odour concentration in the nearby area of this swine farm, a set of variable meteorological data, i.e. 2003 hourly meteorological data from Yorton, Saskatchewan, Canada was used. Since INPUFF2 only accepts 144 time periods in one run, the one year hourly meteorological data were divided into numerous periods of 144 hr each. The average odour concentration over each period was then calculated and the average of all periods was calculated as the annual average concentrations. The other three models could directly use this set of data. The receptor grid was 6 km x 6 k m, with a uniform spacing of 100 m.

Results of annual average odour concentrations are shown in Figure 4.10

. The odour contours for various odour concentrations varies in all directions, with the maximum distances occurring leeward of the prevailing winds in the NW and SE areas.

Schauberger et al. (2002) calculated direction-dependent separation distance by AODM model and found that for the area leeward of the prevailing winds the odour occurrence frequency is higher than the areas leeward of less frequent wind directions. Guo et al. (2005) studied odour occurrence in the same area of this study and found the locations with high odour events were mostly downwind of the prevailing winds from the farm.

The maximum downwind distances for 1, 2, 5, and 10 OU/m^3 are presented in Table 4.8. CALPUFF predicted the greatest distances for all odour levels while INPUFF2's predictions are the lowest. AUSPLUME'S predictions are also higher than that of ISCST3. These results indicated that all the four models' predictions are different and if used to determine setbacks, will result in different setback distances with differences up to 71.4%. If annual average odour concentrations from 1 to 10 OU/m^3 are used as setback criteria, the maximum setback distance will be in the range of 0.3 to 2.3 km, which falls in the recommended setback distances by Canadian Prairie Provinces.

As shown in Table 4.8, AUSPLUME's predictions were higher than that of ISCST3 under variable meteorological conditions while they were lower under steady state meteorological conditions. This was caused by the difference in the minimum wind speed limitations of these two models. AUSPLUME assumes the lowest bound wind speed of 0.5 m/s and it will over-predict when wind speed is less than 0.5 m/s (US EPA, 2000) while the lowest wind speed for ISCST3 is 0 m/s. In the 2003 annual meteorological data file used by this study, there were a total of 457 h that the wind speeds were less than 0.5 m/s, which caused over-predictions by AUSPLUME. Similarly, even though CALPUFF's predictions are close to that of ISCST3 under steady state weather conditions, under variable state weather conditions its predictions were much higher than that of ISCST3. US EPA (1998) obtained similar results and considered these results should come as no surprise as the meteorological assumptions used in formulating the downwind transport of the ISCST3 and CALPUFF effluents and the dispersion from the respective plumes and puffs are different. The accumulation of hour by hour meteorological conditions on the transport of CALPUFF puff is the key for the differences that are produced by these two models and the difference is also compounded by the different treatment of dispersion during calm wind conditions (US EPA, 1998).

Comparing the annual average odour concentrations with the results obtained previously using steady state weather conditions, odour can travel much farther under steady state weather conditions if using the same odour concentration criterion. For example, odour can travel up to 20 km under F1 and up to 8 km under F3 before it is diluted to 10 OU/m^3. However, these kinds of steady state weather conditions seldom occur or only occur for a very short period of time, so the conditions are most unlikely to allow the odour travel to the calculated distances. Zwicke (1998) also reported that ISCST3 over-predicted the 1 hour concentraions based on hourly averaged meteorological data by 2.5 to 10 times as compared to a series of controlled pollutant release and experiments. Fritz et al. (2005) also found that the appropriate time period for the Pasquill-Gifford horizontal dispersion parameter used in Gaussian-based dispersion models varied widely depending on the corresponding meteorological variations, and that basing a 1 h averaged concentration on them might result in overestimated downwind concentrations. These results suggests that we may use different odour concentration criteria for steady state weather conditions, such as F1 to C5, than we use for variable weather conditions, such as annual, seasonal, or monthly hourly weather data. If steady state weather data are used, the acceptable odour concentrations allowed should be set high, for example 75 OU as suggested by Guo et al. (2005) using the OFFSET model. If variable weather data are used, the average odour concentration allowed over a year or a month should be much lower. From the results of this study, odour concentrations of 1 to 10 OU may be used.

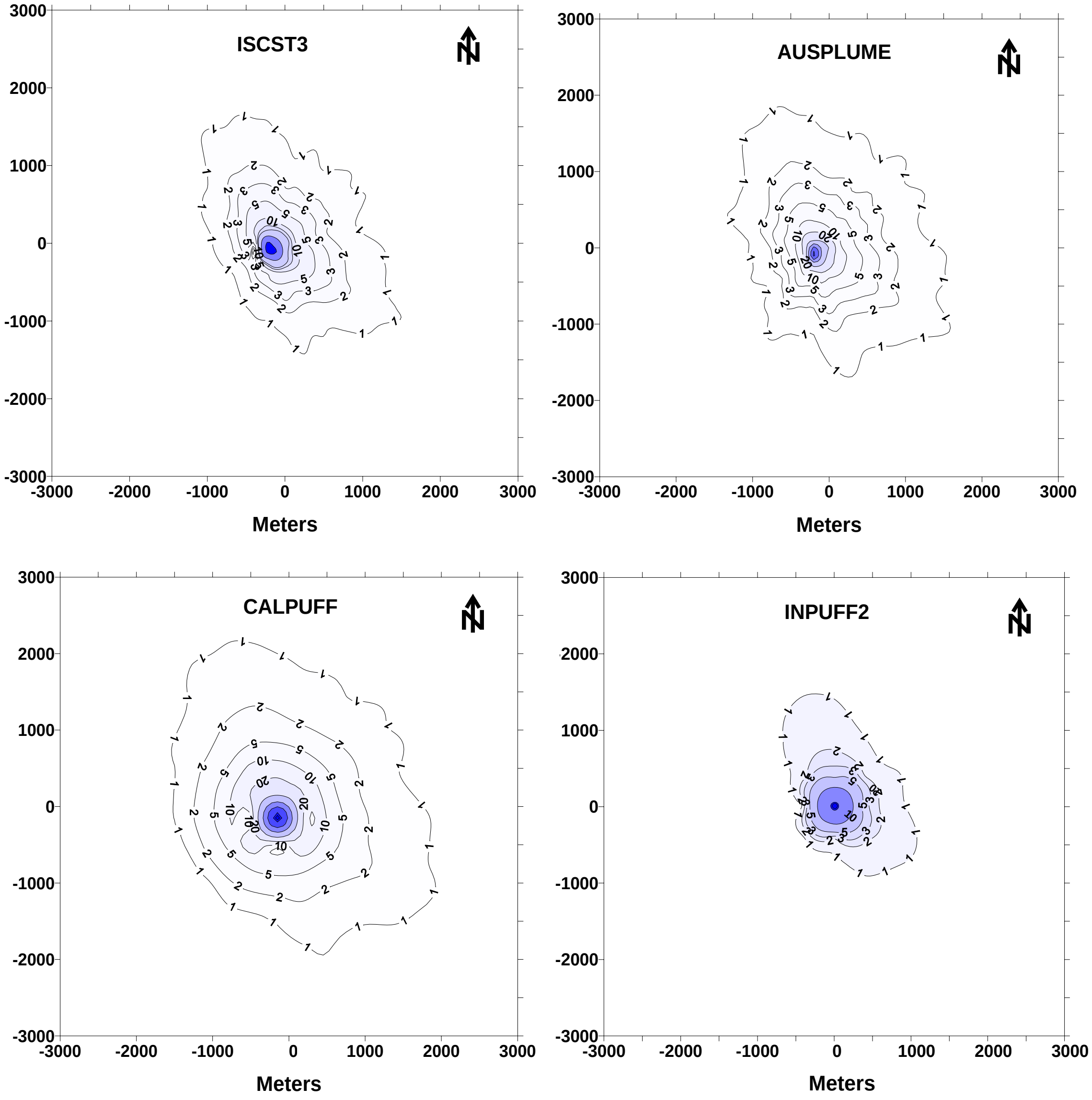


Figure 4.10 Average odour concentration (OU/m^3) for one year simulated by four models

Table 4.8 Maximum distances for different odour levels and model differences based on ISCST3

Odour level (OU/m3)	Odour dispersion models						
	ISCST3	AUSPLUME		CALPUFF		INPUFF2	
	Distance (km)	Distance (km)	Difference (%)	Distance (km)	Difference (%)	Distance (km)	Difference (%)
1	1.8	1.9	7.8	2.3	27.2	1.6	-13.9
2	1.1	1.2	10.2	1.4	28.7	0.8	-29.6
5	0.6	0.7	13.6	0.9	52.5	0.4	-30.5
10	0.4	0.5	19.1	0.7	71.4	0.3	-40.5

4.4 Conclusions

The following conclusions can be drawn from this study:

1. Mixing height has no effect on the odour dispersion for all four air dispersion models.
2. The ambient temperature had significant influences on the odour travel distance as predicted by INPUFF2 but its effect on the other models was very limited. For INPUFF2, the odour travel distance to 10 OU/m^3 increased 34.6 and 47.6% for neutral and stable weather conditions respectively when the temperature increases from -30 to 20^{o}C; while the increases were between 1.9 and 14.8% for the other models. The effect of the ambient temperature gradually reduces with the increase of distance and disappeared at 1 km except INPUFF2.
3. Atmospheric stability has great impact on odour travel distance and all models show similar sensitivity to the changing stability. As the atmospheric stability changed from stable (F1) to unstable (C5), the maximum odour travel distance decreases 95 to 97%. The odour plume centerline concentration at 3 km reduced by 98 to 99% when weather changed from F1 to C5.
4. For each atmospheric stability class, as the wind speed increases, the maximum odour travel distance decreases. Under stability class E, when the wind speed increases from 1 to 5 m/s, the maximum distance decreases by 70 to 79%. Under stability class D, when the wind speed increases from 3 to 8 m/s, the maximum distance decreases by 54 to 67%.
5. Wind direction had a great impact on odour travel distances and odour concentrations near the swine farm. In other words, the source orientation's effect on the odour dispersion is significant especially at close distance downwind.
6. Comparing the model predictions under all steady state weather conditions, ISCST3 and CALPUFF give similar results (within 24.8%) while AUSPLUME and INPUFF2's predictions are much lower than that of ISCST3 (up to 45.3% beyond 0.5 km) for odour concentration and the maximum downwind distance from the source. The differences between the model predictions generally decreased with the increase of instability and wind speed, and generally stabilized beyond 1 km from the source.
7. Using annual hourly weather data, CALPUFF predicted the greatest distances for odour concentrations from 1 to 10 OU/m^3 while INPUFF2 had the shortest distances.
8. Variable weather conditions make AUSPLUME and CALPUFF produce higher predictions than ISCST3 while these two models predicted lower results than ISCST3 under steady state conditions.

9. The odour concentration predictions using steady state weather data were much higher that obtained by variable weather data. When setting odour criterion for setback distance, it is recommended that if steady state weather data are used, the odour concentration should be allowed to set high, for example 75 OU/m^3 as suggested by Guo et al. (2005) in OFFSET model, while if hourly annual or monthly weather data are used, the average odour concentration allowed during a year or a month should be much lower (1 to 10 OU/m^3) depending on neighboring land use.
10. In order to determine proper setback distance, we can have two options with the weather conditions from the sensitivity analysis conclusions. The steady state weather considered the worst situations which make the odour travel for long distance, but in the model simulation, the running time needs to be tried so as to make the odour transport the farthest. The variable weather conditions use the regular meteorological data which is easy to obtain and can be input into the models easily. Therefore, the variable weather conditions were recommended to use in the setback distance determination.

5. EVALUATING COMMERCIAL AIR DISPERSION MODELS FOR ODOUR DISPERSION, PART I: USING SWINE ODOUR PLUME MEASUREMENT DATA FROM UNIVERSITY OF MANITOBA

5.1 Introduction

It is important that the air dispersion models be properly evaluated for livestock odour dispersion simulation before their predictions can be used with confidence. The model evaluation involves comparison of the model's predictions with limited measured field data.

Zhu et al. (1999) presented data evaluating INPUFF2 in predicting downwind odours from animal production facilities. The model was able to predict the downwind odour levels at short distances, such as 100, 200, and 300 m, from the sources with good confidence. At further distance, the accuracy of the prediction reduced. The scaling factor of 35 and 10 was used to adjust the source emission for the odour dispersion. Following this work, Guo et al. (2001) evaluated this model for long-distance odour dispersion during a 4.8 × 4.8 km grid of farmland in southern Minnesota. The same scaling factors as suggested by Zhu et al. (1999) were used. The model performed well in predicting faint odour under stable to slightly unstable weather conditions. However, it underestimated higher odour intensities of 2 and 3. Zhou et al. (2005) calibrated four air dispersion models, ISCST3, AUSPLUME, INPUFF2, and WindTrax using odour plume measurement data 100 to 1000 m from two swine farms. They concluded that these four models performed similarly and predicted downwind odour concentrations with good agreement with field measured results without using scaling factors. Considering that 58.3% of the measured odour intensities were zero, this conclusion may need further examination, because they considered odour intensity level 0, 1, 2, and 3 as the same level in the agreement discussions.

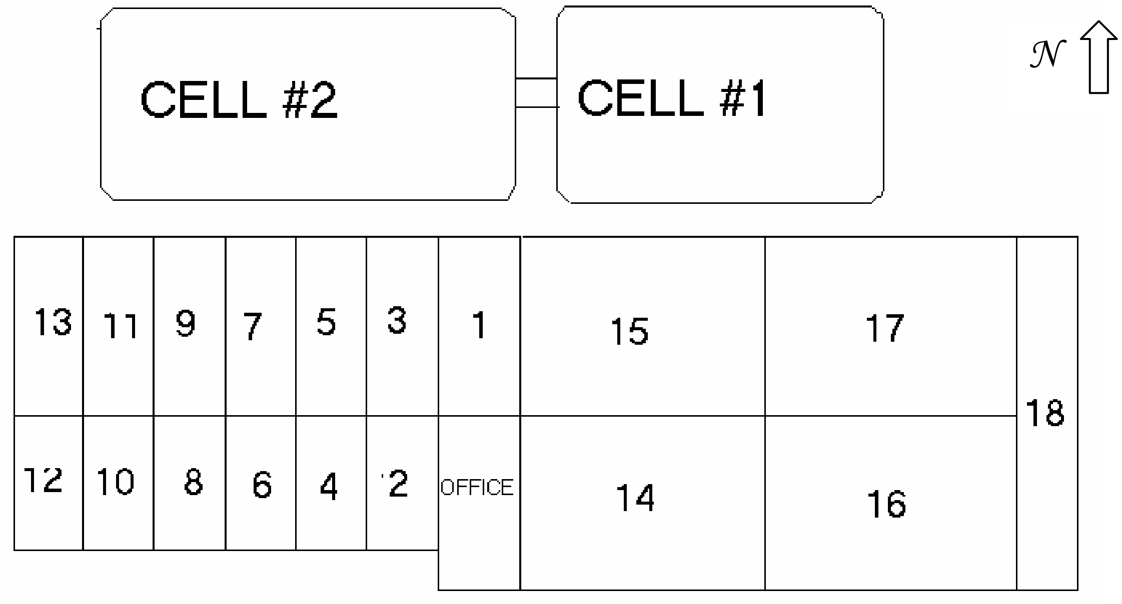
This study was intended to evaluate performances of four commonly used air dispersion models, i.e. ISCST3, AUSPLUME, CALPUFF, and INPUFF2, by comparing their predictions with odour plume measurement data which was the same as Zhou et al. (2005) and to provide recommendations regarding model selection and method for adapting the models in livestock odour dispersion predictions.

5.2 Materials and Methods

5.2.1 Odour plume measurement data

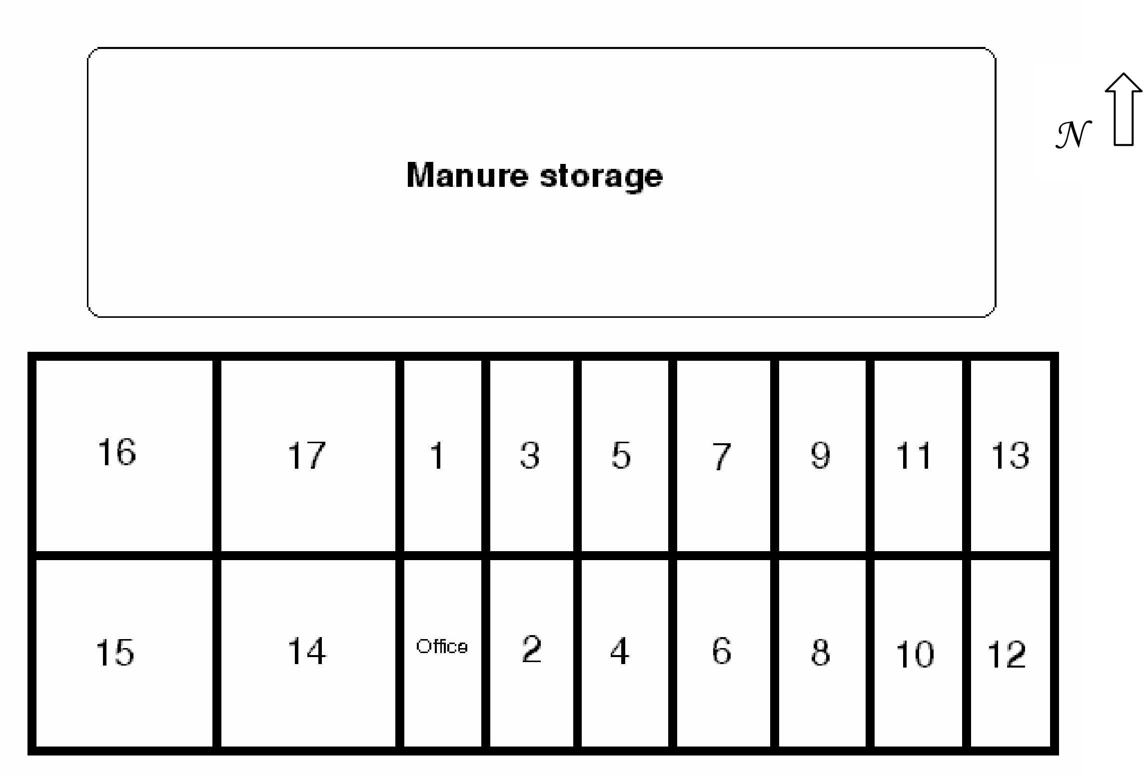
5.2.1.1 Site Description and Odour Emission Rates

Two swine farms were selected for odour plume measurement using trained odour sniffers. The two farms (A and B) were 3000-sow farrowing operations, located in southern Manitoba. The barns on the two farms were identical and were all mechanically ventilated by wall mounted fans. The major difference between the two farms was that Farm A had a two-cell earthen manure storage (EMS) with negative pressure synthetic covers (NPSC) whereas Farm B had an open single cell EMS. Figure 5.1 and 5.2 simply showed the layout of these two farms.



**Room 1 – 13: Farrowing, with 36 individual crates in each room
**Room 14 - 17: Gestation and breeding, 650-sow capacity in each room
**Room 18: Quarantine

Figure 5.1 Layout of the Farm A (Zhang et al., 2005)



**Room 1 – 13: Farrowing, with 36 individual crates in each room
**Room 14 - 17: Gestation and breeding, 650-sow capacity in each room

Figure 5.2 Layout of the Farm B (Zhang et al., 2005)

Detailed descriptions of the two farms are presented in Zhang et al. (2005). The surroundings of the two farms were similar - mostly flat cropland. Odour emission rate was measured during the period of each odour plume measurement (Zhang et al., 2005). The summary of average odour concentrations and emission rates from the measurements conducted during the odour plume measurement periods are given in Table 5.1.

Table 5.1 Odour concentrations and emission rates from barns and manure storages (Zhang et al., 2005)

Odour source		Odour concentration (OU/m^3)		Odour emission(OU/s-m^2)	
		Geometric mean	Standard deviation	Geometric mean	Standard deviation
Farrowing	Farm A	1026	487	22.7	15.2
	Farm B	899	505	23.0	14.4
Gestation	Farm A	927	314	11.6	6.0
	Farm B	799	396	7.6	3.4
NPSC EMS on Farm A	Primary cell	4646	3646	0.7	0.6
	Secondary cell	1991	1568	0.2	0.1
Open EMS on Farm B		769	356	22.4	25.1

5.2.1.2 Downwind Odour Plume Measurement

Fifteen human odour sniffers were selected and trained for conducting field odour measurements (Zhou et al. 2005). The selected sniffers went through a series of six training sessions to use an 8-point ASTM Odour Intensity Reference Scale to quantify the field odour intensity (Table 5.2) (ASTM 1999). For each session before leaving for the field, standard reference n-butanol samples were used to calibrate the sniffers' noses. A base point was selected at the edge of the farm and its position was determined by longitude and latitude readings from a GPS positioning system. Based on the measured wind direction, 15 sniffers were placed in a three-row grid 100, 500, and 1000 m downwind from the base point with the assistance of GPS units (GPS 45, Garmin International, Lenexa, Kansas). At the predetermined grid point, sniffers recorded their exact positions based on the longitude and latitude readings from the GPS units.

Every sniffer followed a central coordinator's instructions to sniff. During each 10 min measurement session, the sniffers put on a carbon filtered air mask to rest his/her nose and sniffed the odour for 10 seconds, and then recorded the odour intensity and odour description. At the end of each session, 60 observations had been recorded by each sniffer. Three measurement sessions were carried out within one hour, with a 10-min break between sessions. Fifty-one field sessions was conducted around the two farms.

Weather data including solar radiation, temperature, relative humidity, and wind speed and direction were taken every minute during the plume measurement period by the on-site weather station (WatchDog Model 550, Spectrum Technologies Inc., Plainfield, IL). The weather station was placed 2 m above the ground to collect weather information during the session. Atmospheric stability of each minute was classified using the Solar Radiation Delta-T (SRDT) Method for Estimating Pasquill-Gifford (P-G) Stability Categories (US EPA, 2000) based on one-minute average solar radiation and wind speed values.

5.2.2 Model Configuration

ISCST V3, AUSPLUME V5.4, CALPUFF V5.0, INPUFF V2.3 were used in this study. AUSPLUME, CALPUFF, and INPUFF2 were all configured with ISCST3's setup options as much as possible, e.g. final plume rise, stack-tip downwash, buoyancy-induced dispersion, usage of calms processing routine, not use missing data processing routine, default wind profile exponents, default vertical potential temperature gradient, "upper bound" values for super squat buildings, no exponential decay for rural mode, and no dry/wet depletions. The barn and the manure were all considered as area sources for ISCST3, AUSPLUME, and CALPUFF, except for INPUFF2 with point sources. ISCST3, AUSPLUME, and CALPUFF used one hour met data taking the average of the minute readings within three sessions in one hour and conducted one hour' simulation time. INPUFF2 used one minute meteorological data directly and simulated 10 minuses at each run which was corresponding to each session's duration time.

5.2.3 Relationship between Odour Concentration and Intensity

As described in 3.2.2, air dispersion models predict odour in concentration while odour intensity is measured in the odour plume measurement (Li, et al., 1994; Hartung and Jungbluth, 1997; Zhu et al., 2000; Guo et al., 2001; Zhang et al., 2005). In this field measurement, 0-8 scale odour intensities were used in the field by the human sniffers. This difference between these two sets of data was needed to be solved in order to validate odour dispersion models, i.e. it is necessary to convert the predicted odour concentration into measured odour intensity levels. To establish this relationship, odour samples collected in Tedlar bags were measured in the Olfactometry lab for both odour intensity and concentration. University of Manitoba and University of Alberta obtained different relationships (Table 5.2). The conversion equation from University of Manitoba and University of Alberta takes the form of equation 3.8 and equation 3.9.

Table 5.2 Odour intensity referencing scale and relationship between odour intensity and odour concentration

		8 point scale			5 point scale by Guo et al. (2001)		
Intensity level	Annoyance	n-butanol solution (ppm)	Odour concentration （OU/m^3） by Zhang et al. (2005)	Odour concentration （OU/m^3） by Feddes et al. (2005)	Intensity level	n-butanol solution (ppm)	Odour concentration （OU/m^3）
0	no odour	0	0	1	0	0	
1	not annoying	120	0	2			
2	a little annoying	240	0.2	5	1	250	25
3	a little annoying	480	3	12			
4	annoying	960	24	26	2	750	72
5	annoying	1940	116	58	3	2250	212
6	very annoying	3880	412	128			
7	very annoying	7750	1204	287	4	6750	624
8	extremely annoying	15500	3051	640	5	20250	1834

When generating equation 3.8 used by the University of Manitoba, only 20 odour samples were collected in Tedlar bags from the farms and presented to trained human panel for odour intensity and odour concentration measurement in the olfactometory lab. However, there were over 100 odour samples used to generate the equation 3.9 used by the University of Alberta. From this point of view, equation 3.9 is more reliable than equation 3.8. Furthermore, the equation 3.8 is not reasonable because intensities 1 to 3 have virtually the same odour concentrations. There are also two problems with the equation 3.9: a) odour concentrations for high intensities levels seem too low, b) low intensity levels have too low odour concentrations. For example, odour concentration of 640 OU/m^3 is at the moderate or low end of odour concentrations measured in swine barns and manure storages in warm seasons, and may not be considered strong comparing with odour measured in the manure storage or from the barns in winter. For comparison purpose, Table 5.2 also gives the odour concentrations of a 5 point n-butanol scale obtained by Guo et al. (2001) at the University of Minnesota. This conversion relationship is very different from the equations 3.8 and 3.9. For example, intensity 1 on this scale is perceived as very faint odour and it is equivalent to intensity 2 for n-butanol concentration-in-water on the 8-point scale, but its swine odour concentration 25 OU/m3 is equivalent to intensity 4 on the 8-point scale represented by equations 3.8 and 3.9. Regarding swine odour concentration, intensity 2 on the 5-point scale is between intensities 5 and 6 in equation 3.9; intensity 3 is between intensities 6 and 7 in equation 3.9, and intensity 4 is equivalent to intensity 8 in equation 3.9. In this study both equations 3.8 and 3.9 will be used to convert the modeled odour concentration to odour intensity.

Also, this part of study will attempt to convert 5-point scale odour intensity and concentration relationship from University of Minnesota into 8-point scale odour intensity and concentration relationship to re-evaluate these four models using Manitoba's plume measurement data. Because the n-butanol in water is fixed value depending on different intensity level (Table 5.2), we used them as the bridge between the 5 point scale and 8 point scale conversions equations. The detail processing procedures were described as followed:

1. Using the last two columns values in Table 5.2, for 5-point ASTM Odour Intensity Reference Scale from University of Minnesota, the relationship between odour concentration and n-Butanol in water is showed in Figure 5.3 as

$$C = 0.1116X^{0.9785} \quad (R^2=1) \qquad (5.1)$$

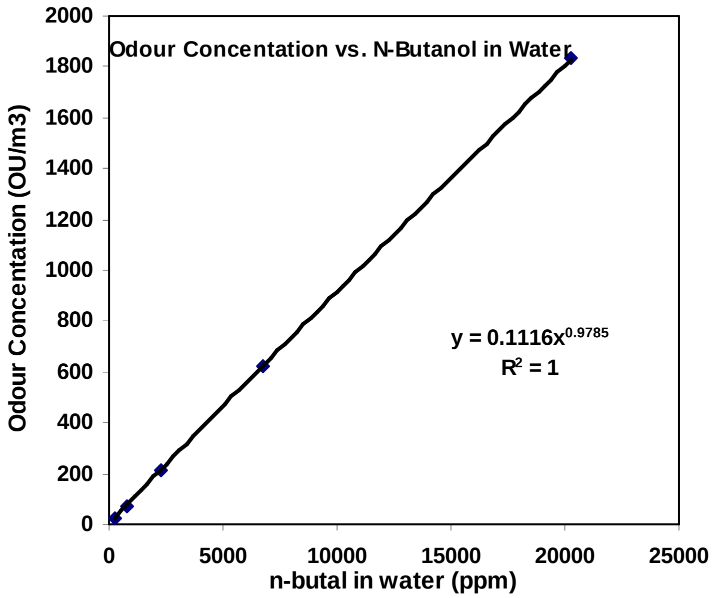


Figure 5.3 Relationship between odour concentration and n-butanol in water

According to the above equation 5.1, we can determine the odour concentration corresponding to 8 point odour intensity reference scale's n-butanol in water and Table 5.3 shows the results.

Table 5.3 8-point odour intensity referencing scale and relationship between odour intensity and odour concentration

Intensity level	n-butanol solution (ppm)	Odour concentration (OU/m3) by using equation 5.1	Odour concentration range (OU/m3)	Odour concentration (OU/m3) by Zhang et al. (2005)	Odour Concentration range (OU/m3)	Odour concentration (OU/m3) by Feddes et al. (2005)	Odour concentration range (OU/m3)
0	0	0	<1	0	0	1	<1
1	120	12	1~17	0	0	2	1~3
2	240	24	17~33	0.2	0~1	5	3~8
3	480	47	33~66	3	1~10	12	8~17
4	960	92	66~130	24	10~56	26	17~39
5	1940	184	130~257	116	56~225	58	39~86
6	3880	363	257~508	412	225~719	128	86~192
7	7750	713	508~1003	1204	719~1946	287	192~428
8	15500	1406	>1003	3051	>1946	640	>428

From the values of first and third columns in Table 5.3, the relationship between odour concentration and intensity can be determined. The Weber-Fechner law model is also used to represent the relationship as showed in Figure 5.4. The equation takes the form of

$$C = 6.1126 \exp(0.68 I) \quad (R^2 = 1) \qquad (5.2)$$

And then the inverse function of (5.2) is

$$I = 1.47\ln(C) - 2.663 \tag{5.3}$$

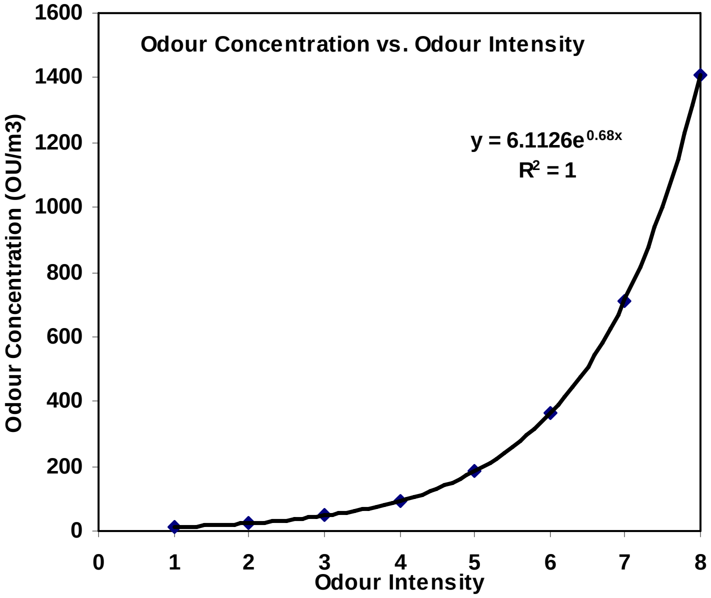


Figure 5.4 Relationship between odour concentration and odour intensity

5.2.4 Comparisons between Model Predictions and Field Measurements

Because field odour intensity was measured in unit of three ten-minute sessions, the measured odour intensity within one hour was averaged as the one-hour average for comparison with ISCST3, AUSPLUME, and CALPUFF models. A total of 817 pairs of data points were compared between the model predictions and field measurements for these three models. Because INPUFF2 could predict one-minute concentration, one minute meteorological data were used in INPUFF2 directly and the predicted values (after converted from concentration to intensity) were compared with the one-minute odour intensity values measured in the field. There were 17640 paired data points obtained.

As the odour intensity measurement uses a categorical scale, one intensity level covers ±0.5 of this level. Hence, if the predicted odour intensity is within ±0.5 of the measured intensity, the predicted value is considered in agreement with the measured value. For example, if the predicted intensity is 1.4 and measured intensity falls into the range between 1.4-0.5 and 1.4+0.5, we consider the predicted value and measured value are in agreement.

5.2.5 Using ASTM-Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model Performance

The 'Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model performance,' published by the American Society of Testing and Materials, provides a framework for developing techniques that are useful for comparison of modeled and observed concentration (ASTM 2000). Research work has been done to the development the performance measures to evaluate the air quality models (Fox 1981, Kumar et al., 1993, and Patel and Kumar 1998). Seven statistical parameters, i.e. Bias, the normalized mean square error (NMSE), the coefficient of correlation (γ), the fraction of predictions with a factor of two of observations (FAC2), the absolute fractional bias (FB), the geometric mean variance (VG), and the Geometric mean bias (MG) have been determined for evaluation model performance (Abdul- Wahab, 2003). In this study, we used the FB as an overall measure. The general expression for the fractional bias (FB) is given by:

$$FB = 2\frac{(PR - OB)}{(PR + OB)} \tag{5.4}$$

Where OB and PR refer to the averages of the observed (OB) and predicted (PR) values. The same expression is used to calculate the FB of the standard deviation where OB refers to the standard deviation of the observed values and PR refers to the standard deviation of the predicted values.

The measure of performance recommended by the U.S. EPA (US EPA, 1992) is the fractional bias screening test as showed in equation 5.4. The FB was selected as a measure of performance in this evaluation because it has two desirable features. First, the fractional bias is symmetrical and bounded, which varies between -2.0 (extreme underprediction) to +2.0 (extreme overprediction) and has an ideal value of 0 for an ideal model. Second, the fractional bias is a dimensionless number, which is convenient for comparing the results from studies involving different concentration levels, or even different chemical parameters. A Value of -0.67 is equivalent to model underprediction by a factor of two, while v +0.67 is equivalent to overprediction by a factor of two. Model predictions with a fractional bias of 0 (zero) are relatively free from bias. A low variance in FB can be taken as indicating confidence in the model prediction (McHugh et al., 1999). The FB between predicted intensity and measured intensity was calculated to evaluate the models' performance.

5.3 Results and Discussions

5.3.1 Using Conversion Equation from University of Manitoba

For equation 3.8, the intensities 1, 2, and 3 had almost the same odour concentrations between 0 and 3 OU/m^3 (Table 5.2), so they were considered as the same intensity level (intensity 1-3) because it is difficult for human noses to distinguish the odour intensities with odour concentrations of 12 OU/m^3 or less. Table 5.4 summarized the overall agreements after the predicted odour concentrations were converted into intensity by using the equation 3.8 for all models. For all four models, the percentages of agreements were low at 100 m distance but much higher for 500 and 1000 m (Table 5.4). Because the property line of swine farms are usually beyond 100 m, the downwind distances of 500 and 1000 m are of the most interest. Furthermore, the air dispersion models are not designed to predict downwind concentrations at such a short distance. If all measurements were considered, the three models, ISCST3, CALPUFF, and INPUFF2 performed similarly with agreement between 70% (ISCST3 and CALPUFF) and 74% (INPUFF2) for 500 to 1000 m, and overall agreement of 58% (ISCST3 and CALPUFF) to 61% (INPUFF2). AUSPLUME had lower agreement of 65% for 500 to 1000 m and 56% for all the measurements.

However, if we only consider the measurements with odours detected, i.e. excluding all the measurements with zero intensity, then the agreements of the modeled and measured values reduced as given in Table 5.5. The AUSPLUME model performed the best with 25% total agreement and CALPUFF has the following better agreement with 23% while they have the same agreement for distance 500 to 1000 m (14%). The other two models had agreements between 8% to 11% for 500 to 1000 m, and 13% to 19% overall agreement. Considering the uncertainties in field odour plume measurement and the odour dispersion modeling, including a) the high uncertainty in odour intensity measurements by human sniffers, b) the uncertainty of using the average of the three 10-min session odour plume measurement in one hour, c) the odour emission measurements, d) the uncertainty in odour concentration and intensity conversion equation 3.8, etc., the obtained agreements are satisfactory.

Table 5.4 Percentage of agreement between model predictions and field measurements for all field measurements including intensity level 0 using equation 3.8

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	31	35	30	28
500 m	55	50	55	62
1000 m	85	81	85	86
500 to 1000 m	70	65	70	74
Overall	58	56	58	61

Table 5.5 Percentage of agreement between model predictions and field measurements for all field measured odours (not including intensity level 0 odour measurements) using equation 3.8

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	23	30	25	13
500 m	17	19	23	16
1000 m	0	9	4	6
500 to 1000 m	8	14	14	11
Overall	19	25	23	13

5.3.2 Using the Conversion Equation from University of Alberta

As stated previously, the equation 3.9 could be more reliable than the equation 3.8, therefore, we also used the conversion equation 3.9 to analyze this set of data. The odour intensity levels 1 to 3 were still considered as the same level intensity.

Table 5.6 summarized the overall agreements for all odour measurements including zero intensity. All models performed similarly and the agreement ranged from 67% (AUSPLUME) to 76% (INPUFF2) for 500 to 1000 m, and 57% (CALPUFF) to 62% (INPUFF2) for all distances. The agreements are similar with the agreement using University of Manitoba equation 3.8.

If measurements with zero odour intensity were excluded, as given in Table 5.7, however, the agreements were much lower. For 500 to 1000 m, the agreement ranged between 5% (ISCST3) and 13% (AUSPLUME) while the agreement for all measurements ranged between 12% (INPUFF2) and 23% (AUSPLUME). CALPUFF and AUSPLUME performed better than ISCST3 and INPUFF2. Comparing with the agreements (excluding 0 intensity) obtained by using the equation 3.8, the agreements are lower. This is opposite of the results for all measurements including zero odour intensity. The reason is the difference between the equations 3.8 and 3.9 in the low intensity levels 0 to 2. By using the equation 3.9, the odour concentration for intensities 1 and 2 are higher than that by the equation 3.8, therefore, the agreement for measured intensity zero increased using equation 3.9, which in turn decreased the agreement of higher intensities.

Table 5.6 Percentage of agreement between model predictions and field measurements for all measurements including intensity level 0 using equation 3.9

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	27	36	28	28
500 m	52	52	55	63
1000 m	88	82	86	89
500 to 1000 m	70	67	70	76
Overall	58	57	58	62

Table 5.7 Percentage of agreement between model predictions and field measurements for all measurements excluding intensity level 0 using equation 3.9

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	18	31	22	12
500 m	11	13	19	15
1000 m	0	13	4	3
500 to 1000 m	5	13	11	9
Overall	15	23	19	12

5.3.3 Using the 8 Point Scale Conversion Equation Converted with 5 Point Intensity Scale from University of Minnesota

To be consistent with the above analysis methods, we also conducted another agreement which combined the odour intensity 1, 2, and 3 as the same level. On the other hand, according to the odour concentration range showed in Table 5.2, the odour concentration from intensity level 1 to intensity 3 for 8 point scale odour intensity in Table 5.3 all fell into the odour concentration range corresponding to the intensity level 1 on 5 point scale odour intensity shown in Table 5.2. This reason also made sense in combining the above three intensity levels as the one level. Table 5.8 summarized the agreements after the predicted odour concentrations were converted into intensity by using the equation 5.3 for all models with all measurements considered. For all four models, the percentages of agreements were low at 100 m distance, similar to the previous results. Among these four models, INPUFF2 performed best with agreement 74% for 500 to 1000 m and 60% for overall agreement. The other three models, ISCST3, AUSPLUME and CALPUFF performed similarly with agreement between 68% (AUSPLUME) and 71% (ISCST3 and CALPUFF) for 500 to 1000 m, and the same overall agreement of 60%. These results were similar with that obtained using conversion equations from University of Manitoba's and University of Alberta.

However, if we only consider the measurements with odours detected, i.e. excluding all the measurements with zero intensity, then the agreements of the modeled and measured values reduced as given in Table 5.9. The AUSPLUME model performed the best with 17% agreement for distance 500 to 1000 m and 29% for all distances followed by CALPUFF (11% for distance from 500 to 1000 m and 25% for all distances) while the other three models just had the agreement 9% (ISCST3 and INPUFF2) and 11% (CALPUFF). INPUFF2 had the lowest agreements among these four models. Comparing with the previous results in Table 5.5 (using conversion equation from University of Manitoba) and Table 5.7 (using conversion equation from University of Alberta), for distance from 500 to 1000 m, ISCST3 and AUSPLUME performed better than that in Table 5.5 and 5.7 while CALPUFF and INPUFF2 agreements were lower. For overall agreements, ISCST3, AUSPLUME, and CALPUFF all performed better than the previous results in Table 5.5 and 5.7 except INPUFF2's agreements were lower. To sum up, the models' agreements using equation 5.3 were better than that obtained using equation 3.8 and 3.9 without considering the odour intensity level 0 in the field measurements. However, the equations 5.3 did not show obvious better performance than the other two equations.

Table 5.8 Percentage of agreement between model predictions and field measurements for all measurements including intensity level 0 using equation 5.3

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	34	40	34	26
500 m	56	53	57	62
1000 m	85	83	85	86
500 to 1000 m	71	68	71	74
Overall	60	60	60	60

Table 5.9 Percentage of agreement between model predictions and field measurements for all measurements excluding intensity level 0 using equation 5.3

Downwind distance	Agreement (%)			
	ISCST3	AUSPLUME	CALPUFF	INPUFF2
100 m	27	35	29	10
500 m	18	21	23	13
1000 m	0	13	0	5
500 to 1000 m	9	17	11	9
Overall	22	29	25	10

Table 5.10 and 5.11 compares the agreements of each intensity level using equations 3.8 and 5.3 for models AUSPLUME and INPUFF2. The main reasons for the higher agreements of AUSPLUME using equation 5.3 than that obtained by equation 3.8 are that values ranges for intensities 1-3 of the equation 5.3 are much higher than equation 3.8 and AUSPLUME gave the better predictions in this value range using equation 5.3 than using equation 3.8. Furthermore,

odour intensity level 1-3 occupied 30.8% in all field measurements which means good agreements in this range will make the overall agreements better. In Table 5.11, INPUFF2 gave a little bit lower (almost the same) agreements by equation 5.3 than equation 3.8 mainly because INPUFF2 showed worse predictions for intensity level higher than 3 but good for intensity level 1-3 which caused similar overall agreements. These results in Tables 5.10 and 5.11 indicated that the conversion equations from University of Manitoba (equation 3.8) performed better for high level intensity level (>3) than the relationship from University of Alberta (equation 3.9) and University of Minnesota (equation 5.3). Further more, the details of agreements in Appendix A also showed that the predicted intensities using conversion equation 3.9 and 5.3 were lower than measured ones for most data points especially for high level odour intensity while about half points of the predicted intensity with equation 3.8 were higher than the measured ones and the other half points were lower. This indicted that relationship between odour concentration and intensity from University of Manitoba was more suitable for predicting the odour intensity level higher than 4.

Table 5.10 Comparing AUSPLUME for equations 3.8 and 5.3

Measured odour intensity	Total # of data	% of Each level	Equation 5.3 odor concentration Range (OU)	AUSPLUME Equation 5.3 Percentage of agreement (%)	Equation 3.8 Odor Concentration Range (OU)	AUSPLUME Equation3.8 Percentage of agreement (%)
1-3	252	30.8	1~66	38.9	0.1-10	31.0
4	41	5.0	66~130	0.0	10~56	14.6
5	28	3.4	130~257	0.0	56~225	0.0
6	14	1.7	257~508	0.0	225~719	0.0
7	5	0.6	508~1003	0.0	719~1946	0.0
8	1	0.1	>1003	0.0	>1946	0.0
1-8	341			28.7		24.6
0-8	817			59.7		56.2

Table 5.11 Comparing INPUFF2 for equations 3.8 and 5.3

Measured odour intensity	Total # of data	% of each level	Equation 5.3 odor concentration Range (OU)	INPUFF2 Equation 5.3 Percentage of agreement (%)	Equation 3.8 Odor Concentration Range (OU)	INPUFF2 Equation3.8 Percentage of agreement (%)
1-3	4587	26.0	1~66	19.0	0.1-10	17.5
4	787	4.5	66~130	0.9	10~56	9.0
5	624	3.5	130~257	0.1	56~225	1.0
6	429	2.4	257~508	0.0	225~719	0.0
7	198	1.1	508~1003	0.0	719~1946	0.0
8	36	0.2	>1003	0.0	>1946	0.0
1-8	6661			10.5		13.2
0-8	17640			60.1		60.5

5.3.4 Adjusting the Modeled Results Using Scaling Factors

Due to the inherent differences in livestock odour and industrial gases and the different measurement methods for odour and gases, the modeled results obtained by the air dispersion models for odour dispersion should be adjusted to improve the agreements of modeled and measured odour intensities. It is a common practice for odour research to use scaling factors on the modeled odour concentration at the receptors' locations to minimize the error between the modeled values and the odour measurement values. Barns and manure storages may have different scaling factors as suggested by Zhu et al. (2000). The adjusted odour concentration by an air dispersion model is obtained by:

$$C = a \times (\text{modeled odour concentration from building source}) + b \times (\text{modeled odour concentration from manure storage source}) \qquad (5.5)$$

where: C = adjusted odour concentration, OU/m^3, and a, b = constants, i.e. scaling factors for barn and manure storage, respectively.

A small FORTRAN loop was used to calculate the best scaling factor so as to achieve the maximum agreement using all the paired data for different models. We initiated a and b with value 1 and then use equal step +0.1 to increase the two constants until both of them reach 35, the maximum scaling factor obtained by Zhu et al. (2000). For each values a and b, there was an agreement. After comparing these agreements, we can get the maximum agreement and the corresponding values for a and b were the scaling factors that we used for the results improvements.

This analysis was conducted for pairing data obtained by the equation from University of Alberta. During this adjustment, we excluded the pairs of data points with measured intensity "0", i.e. only considered the data when the odour sniffers smelled swine odours in the field. Therefore, the agreements obtained are for measured odour intensities 1 to 8. Furthermore, intensities 1 to 3 were considered as one intensity level (intensity 1-3) because of the small difference of these intensities regarding odour concentration.

The scaling factors are listed in the Table 5.12. Table 5.13 gives the original agreements and the adjusted agreements using scaling factors for all four models. After adjustment, the agreements were only increased by 2 to 5% for all measurements and 2 to 12% for measurement from 500 to 1000 m. AUSPLUME improved the most. This indicated that using scaling factors is not very effective for model performance improvement. The modeled odour concentrations by Zhu et al. (2000) and Guo et al. (2001) were consistently lower than the measured values, which made it possible for using scaling factors (a=35 for building sources and b=10 for manure storage sources) to improve the model performance. However, this did not occur in this study. As indicated in Appendix A that gives the agreement of measured and models' predicted odour intensities for all measurements, the model predicted values were sometimes lower than the measured values and sometimes higher. This occurred to all the models. Hence, the agreements between the model predictions and measured values could not be improved considerably by using scaling factors.

Table 5.12 Scale factors for all four models with equation 3.9

Model	Scale Factor	
	Barn	Manure storage
ISCST3	1.5	2.2
AUSPLUME	1.2	1.4
CALPUFF	1.6	1.8
INPUFF2	2.3	7.9

Table 5.13 Agreements of the original results (unadjusted) and after using scale factor with equation 3.9

Downwind distance	Agreement (%)							
	ISCST3		AUSPLUME		CALPUFF		INPUFF2	
	Original	Modified	Original	Modified	Original	Modified	Original	Modified
100 m	18	23	31	30	22	25	12	13
500 m	11	16	13	28	19	23	15	17
1000 m	0	0	13	9	4	4	3	10
500 to 1000 m	9	14	13	25	18	20	13	16
Overall	14	19	23	28	20	23	13	15

The paired data obtained by the equation 5.3 from University of Minnesota was also analysis using scaling factors. The scaling factors are listed in the Table 5.14 which ranged from 1.1 to 28.8. Table 5.15 gave the original agreements and the adjusted agreements using scaling factors for all four models with the equation 5.3. After adjustment, the agreements were only increased by 2 to 5% for all measurements and 2 to 13% for measurement from 500 to 1000 m. AUSPLUME and CALPUFF both had the best improvement for measurement from 500 to 1000 m (13%) and all distances (5%). The scaling factors were still not very useful in this part. The reasons were similar to that using equation 3.9.

Table 5.14 Scaling factors for all four models with equation 5.3

Model	Scale Factor	
	Barn	Manure storage
ISCST3	1.1	1.3
AUSPLUME	7.4	28.8
CALPUFF	7.3	9.4
INPUFF2	1.2	18.9

Table 5.15. Agreements of the original results (unadjusted) and after using scale factor (without considering intensity 0) with equation 5.3

Downwind distance	Agreement (%)							
	ISCST3		AUSPLUME		CALPUFF		INPUFF2	
	Original	Modified	Original	Modified	Original	Modified	Original	Modified
100 m	27	30	35	33	29	31	10	15
500 m	18	19	21	39	23	31	13	16
1000 m	0	0	13	22	0	17	5	5
500 to 1000 m	9	10	17	30	11	24	9	11
Overall	22	24	29	34	25	30	10	15

5.3.5 Using ASTM-Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model Performance

This analysis was conducted from 817 pairs of intensity data for ISCST3, AUSPLUME, and CALPUFF, and 17640 pairs of INPUFF2 intensity data obtained by the equation 3.8 from University of Manitoba. The bias analysis results for the four models are presented in Figure 5.5. In general, ISCST3 performs the best with the lowest bias in matching field measured odour intensity followed by AUSPLUME. CALPUFF and INPUFF2 also performed well within FB value lower than 0.67. However, CALPUFF over predicted by bias of average intensity while INPUFF2 under predicted by a value of -0.66 of the bias of average.

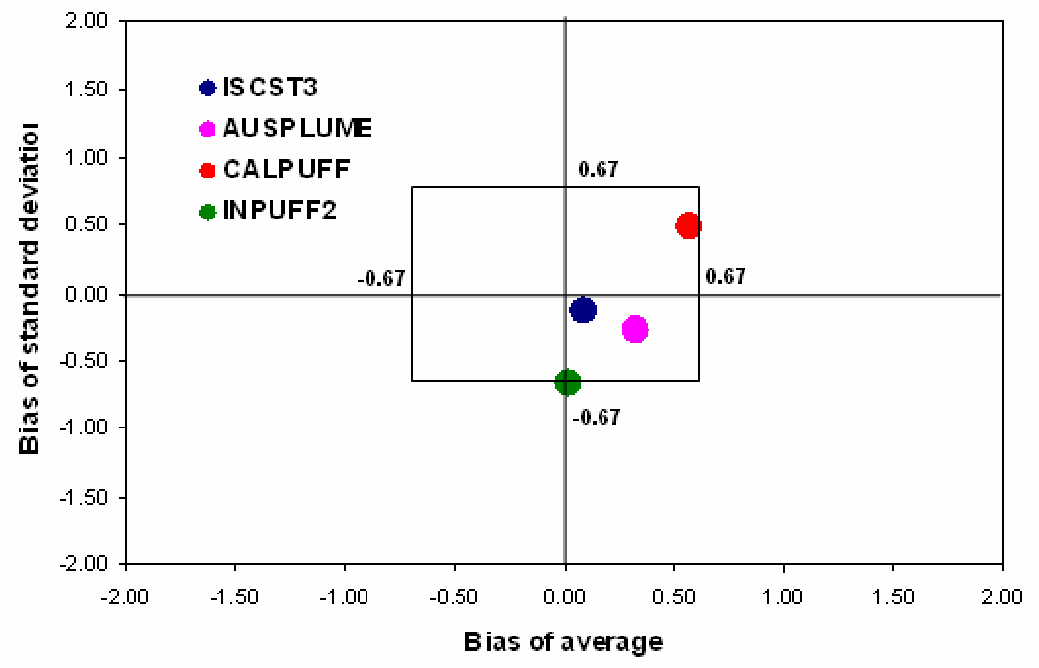


Figure 5.5 Bias analysis results for the models

5.4 Conclusions

1. Considering all the measurements taken and using the odour intensity and concentration conversion equation generated by University of Manitoba, the predictions of the four models, i.e. ISCST3, AUSPLUME, CALPUFF, and INPUFF2, achieved 56% to 61% of agreement with the measured odour intensities for distances of 100 to 1000 m, and 65% to 74% for distance of 500 to 1000 m. INPUFF2 performed the best while AUSPLUME performed worst. However, if the measurements with intensity zero (no odour) were excluded, the agreement reduced to 13 to 25% for all distances and 8 to 11% for distance of 500 to 1000 m.
2. Considering all the measurements taken and using the odour intensity and concentration conversion equation generated by University of Alberta, the predictions of all models were similar with 56 to 62% of agreement with the measured odour intensities for all distances, and 67 to 76% for distance of 500 to 1000 m, which are similar with that obtained using the University of Manitoba conversion equation. INPUFF2 performed the best. However, if the measurements with intensity zero (no odour) were excluded, the agreement reduced to 13 to 23% for all distances and 9 to 18% for distance of 500 to 1000 m, which are lower (almost the same) than that obtained using the University of Manitoba conversion equation.

3. Considering all the measurements taken and using the 8 point intensity scale conversion equation generated from the 5 point scale relationship by University of Minnesota, INPUFF2 performed best with agreement 74% for 500 to 1000 m and 60% for overall agreement. The other three models, ISCST3, AUSPLUME and CALPUFF performed similarly with agreement between 68% (AUSPLUME) and 70% (ISCST3 and CALPUFF) for 500 to 1000 m, and overall agreement from 56% (AUSPLUME and CALPUFF) to 57% (ISCST3). If the measurements with intensity zero (no odour) were excluded, the agreements reduced to 10% to 20% for all distances and 8% to 16% for the distance of 500 to 1000 m.
4. Considering all the measurements and comparing the agreements using different conversion equations, the agreements using different equations were close with each other for the overall agreement from 56% to 62% to all the field measurements and range from 10% to 29% without considering odour intensity level “0”.
5. If we only considered the measurements with odours detected, i.e. excluding all the measurement with zero intensity, and comparing the agreements using different conversion equations, the agreements using the equations from University of Alberta and University of Minnesota were still similar and University of Manitoba’s conversion equation performed better than the other two. The difference indicated that equation 3.8 from University Manitoba is more suitable for predicting the high level odour intensity than the other two equations.
6. Due to the inherent differences in livestock odour and industrial gases and the different measurement methods for odour and gas, scaling factors were generated to adjust the modeled results to improve the agreements of modeled and measured odour intensities. The scaling factor ranged from 1.2 to 7.9 by using the equation from University of Manitoba. The agreement was improved only by 2 to 12%. For equation from University of Minnesota, the scaling factor ranged from 1.1 to 28.2 and the agreement was increased by 2 to 15%. The lower improvement indicted that the scaling factor is not very useful for the results improvement because not all the model predictions were lower than the field measurements.
7. Using ASTM Standard Guide for air dispersion model evaluation with the application of equation 3.8 from University of Manitoba, ISCST3 performs the best with the lowest bias in matching field measured odour intensity followed by AUSPLUME. CALPUFF and INPUFF2 also performed well within FB value lower than 0.67. However,

CALPUFF over-predicted by bias of average intensity while INPUFF2 under predicted by a value of -0.66 of the bias of average.

8. Considering the overall performance of the four models, no model stood out with better performance. CALPUFF and AUSPLUME performed better than ISCST3. INPUFF2 could be used for simulation of odours with short measurement time intervals (<1 hr), however, the simulation time interval should be chosen as one measurement session, e.g. 10 min, instead of 1 min.
9. The odour intensity and concentration conversion equation is very important to ensure the accuracy of the comparison of the modeled and measured odour intensities. The effectiveness of improving model performance using scaling factors needed to be further examined.

6. EVALUATING COMMERCIAL AIR DISPERSION MODELS FOR ODOUR DISPERSION, PART II: USING SWINE ODOUR PLUME MEASUREMENT DATA FROM UNIVERSITY OF MINNESOTA

6.1 Introductions

According to the research work done by Zhu et al. (1999) and Guo et al. (2001) from University of Minnesota, the scaling factor of 35 and 10 was used to adjust the source emission for the odour dispersion modeling to amplify model predictions so that they would fall into the same numerical range as the field measurement data. However, in the evaluation work using the swine plume measurement data from University of Manitoba, the scaling factors were not very useful for the results improvement. Therefore, this part of study was intended to recheck the results with University of Minnesota odour plume measurement data

6.2 Materials and Methods

6.2.1 Model Selection

Air dispersion models CALPUFF and INPUFF2 were used for the odour dispersion modeling in this part. In the chapter 4 and 5, CALPUFF and ISCST3 always predicted the similar values and CALPUFF predicted the highest value under variable weather conditions in the sensitivity study. Further more, CALPUFF is the US EPA preferred model. INPUFF2 was evaluated in Zhu et al. (1999) and Guo et al. (2001) using the plume measurement data from University of Minnesota and it can take the actual field measurement time interval such as 10 seconds or 1 minute. Therefore, we only used these two models to conduct the simulations.

6.2.2 Site Description and Odour Emission Rates

For the experiments, a total of 28 farm sites were measured in Minnesota, which covered most of the animal species (Zhu et al., 1999). In this study, we only selected several typical sets of data measured on ten of farms to conduct the simulations. Some farms only barns were measured and others only EMS were measured, and some farms barns and EMS were both measured. The surroundings of the farms were all considered as mostly flat cropland free of obstacle. Odour emission rates were measured during the period of each odour plume measurement (Zhu et al., 1999). The summary of average odour concentrations and emission rates from the measurements are given in Table 6.1. The modified emission rates with scaling factor (35 for barn and 10 for EMS) were input into the models to conduct the simulations.

Table 6.1 Original measured odour emission rates and modified emission rates after using scale factors for different farms in Minnesota

Source	Measurement time	Original emission rate (OU/m^2/s)	Modified emission rate (OU/m^2/s)	Original total emission rate (OU/s)	Modified total emission rate (OU/s)
Farm 1	Day 203-Morning	41.3	413.0	320134	3201343
EMS	Day 203-Afternoon	26.7	267.2	207118	2071179
Farm 2	Day 217-Morning	4.4	44.5	8106	81058
EMS	Day 217-Afternoon	7.7	77.3	14102	141018
Farm 3 Barn	Day 219-Morning/Afternoon	1.7	60.2	998	34937
Farm 4 EMS	Day 220-Morning/Afternoon	6.5	65.3	27747	277465
Farm 5	Day 221-Morning	1.7	58.1	298	10422
EMS	Day 221-Afternoon	11.9	414.8	2125	74390
Farm 6 EMS	Day 222-Morning	1.7	60.6	1327	46457
Farm 7 Barn	Day 223-Morning/Afternoon	2.5	86.7	4727	165431
Farm 7 Barn	Day 223-Morning/Afternoon	3.0	104.1	5672	198517
Farm 8 Barn1	Day 224-Morning/Afternoon	6.9	241.2	5286	185008
Farm 8 Barn2	Day 224-Morning/Afternoon	7.0	243.8	5343	187019
Farm 9 Barn1	Day 77-Morning	31.3	1096.8	23178.01	811230
Farm 9 Barn2	Day 77-Morning	20.5	717.9	15170.59	530971
Farm 10 EMS	Day 275-Morning	17.2	171.51	102907	1029070
Farm 10 Barn	Day 275-Morning	0.5	19.08	2927.29	102455

6.2.3 Downwind Odour Plume Measurement

According to the experiments descriptions in Zhu et al. (1999), seven pre-selected human sniffers were trained using intensity rating scale of 0 to 5 to describe the odour and then taken to the field to conduct on-site odour intensity measurement. Jacobson et al. (1998) presented the detailed measurement procedures. In the field, distances between 50 to 500 m (depending on site and strength of odour source) were marked off at the approximate centerline of the downstream odour plume. Perpendicular to this centerline, straight lines were marked off to locate individual sniffers with marker flags from between 5 to 20 m apart (depending upon the plume width) so that the seven individual sniffers would approximately cover the plume width. Human sniffer scores were taken every 10 s for a period of 10 min session. In this study, a total of 30 sessions of data taken over 8 different days in 1998 and 6 sessions of data for 2 days in 1999 were obtained from University of Minnesota. For each of the days, two or three sessions of data were taken in the morning and afternoons, each session at a different short distance (25-300 meter) downwind of the odour source.

At each site, a portable weather station was set up 2 m above the ground to record on-site weather information including wind speed and direction, solar radiation, temperature, recording time, and relative humidity. The meteorological data were recorded at 10-s intervals to match the frequency of the downwind odour intensity records data collected by the human sniffers.

6.2.4 Relationship between Odour Concentration and Odour Intensity

In Guo et al. (2001), for the experiment in Minnesota (long distance; trained residents monitoring), the relationships between odour intensity 0 to 5 scale and concentration are expressed as equation 3.6 which was used in the data analysis.

6.2.5 Comparisons between Model Predictions and Field Measurements

Because field odour intensity was measured in 10 s interval within 10 min session, the average of the measured odour intensity within one session was considered as the one-hour average for comparison with CALPUFF predictions. For CALPUFF models, the meteorological data with 10-s interval in one session were averaged as one hourly data and then input into the models to conduct the simulations. Although INPUFF2 can use 10-s meteorological parameters to predict 10-s average odour concentration, to be consistent with the CALPUFF simulation, INPUFF was used to calculate every 10-s odour concentration during each 10 min session, but 10-s odour concentrations within 10 min session were averaged to be compared with the 10 min measured average odour intensity. Therefore, for these two models, we all compared 10 min average data. Further more, only the centerline of the nasal rangers' layout in the data of 1998 could be ratified, so there was total 30 paired data points. For the data of 1999, all the nasal rangers' locations can be determined, so there will be 42 pairs of data points. Totally, there were 72 pairs of data used for the model evaluation. All the data were divided into groups by the distances from the sources, i.e. 100, 200, 300 m.

6.3 Results and Discussions

6.3.1 Agreements Analysis

Considering all the measurements, Table 6.2 summarized the overall agreements after the predicted odour concentrations were converted into intensity by using the equations 3.6 for CALPUFF and INPUFF2 and Appendix B presents the detail results of the agreement calculation. INPUFF2 have better agreement of 46% than CALPUFF (32%) for the distance of 100 m. These two models had the same agreement of 33% for distance 200 m. However, there was no agreement for 300 m because there were only two pairs of data from distance of 300 m which can not represent the general results. INPUFF2 had better overall agreement of 44% than CALPUFF with overall agreement 31%. Comparing with the previous results in Chapter 5 for short distance these two models performed better with the conversion equation from University of Minnesota. But for any distance under 500 m, the models were all weak.

If we only considered the odour detected, i.e. excluded the odour intensity level 0, as given in Table 6.3, the agreements were a little bit lower than those in Table 6.2. INPUFF2 performed better than CALPUFF for distance 100 m (43%) and 200 m (42%) and overall agreement of 43%. For 300 m, there were still no agreements between predicted intensity and measured one. Hence, INPUFF2 had better performance than CALPUFF.

Table 6.2 Agreement between model predictions and field measurements for all field measurements with equation 3.6

Downwind distance	Agreement (%)	
	CALPUFF	INPUFF2
100 m	32	46
200 m	33	33
300 m	0	0
Overall	31	44

Table 6.3 Agreement between model predictions and field measurements excluded the odour intensity level "0" with equation 3.6

Downwind distance	Agreement (%)	
	CALPUFF	INPUFF2
100 m	28	43
200 m	25	42
300 m	0	0
Overall	26	42

6.3.2 Discussion on the Effect of Scaling Factors

Comparing with previous analysis using the plume measurement data from University of Manitoba, the scaling factor was useful in this part and the main reasons caused the difference are probably: a) the total emission rates of the barn and the manure storage measured in Minnesota (Table 6.1) were much lower than the ones measured in Manitoba's data (Table 5.1), each run for the simulation using the plume measurement data from University of Manitoba included one barn and two manure storage basin while there was only one single or two same odour sources at each specific site in Minnesota, which resulted in much lower total emission rates for each simulation; and b) in this study, the models' performances were only evaluated in short distance (less than 300 m), but longer distances further than 500 m were also used for the model evaluation with Manitoba's plume measurement data. Further more, the agreements using swine plume measurement data from University of Manitoba in Appendix A indicated the models' prediction were also lower than the measured intensities for short distance around 100 m where high level odour intensity occurred. That mean, if we only analysis the models' performance in short distance, the scaling factor might be more useful for the agreement improvement.

6.2.3 Using ASTM-Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model Performance

The bias analysis results for the four models are presented in Figure 6.1. In general, for both CALPUFF and INPUFF2, the biases fell into the acceptable range (-0.67 ~ 0.67). To compare these two models, INPUFF2's bias was 0.05, which means there is little bias between model predictions and field measurements. Hence, INPUFF2 performed better than CALPUFF.

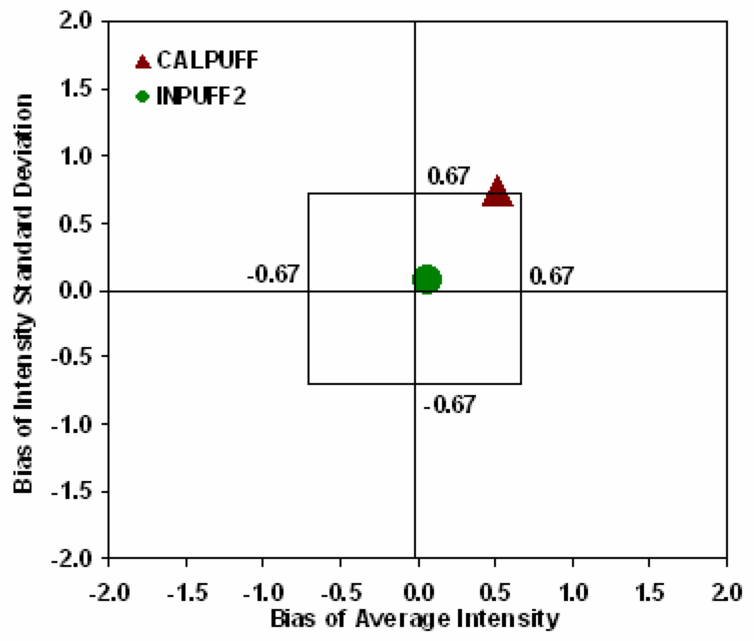


Figure 6.1 Bias analysis results for CALPUFF and INPUFF2

6.4 Conclusions

1. Considering all the measurements, INPUFF2 have better agreement (46%) than CALPUFF (32%) for the distance 100 m and they had the same agreement of 33% for distance 200 m. INPUFF2 had better overall agreement of 44% than CALPUFF (overall agreement 31%). Comparing with the previous results for short distance these two models performed better with the conversion equation from University of Minnesota.
2. If we only considered the odour detected, i.e. excluded the odour intensity level 0, the agreements were only a little lower than the agreements with all field measurements. INPUFF2 performed better than CALPUFF for distances 100 m (43%) and 200 m (42%) and overall agreement (43%).
3. Comparing with previous analysis using the plume measurement data from University of Manitoba, the scaling factors are more effective in this part. The main reason might be the lower total emission rates measured in Minnesota than those in Manitoba.
4. When using the ASTM Standard to evaluate the models' performance, INPUFF2 performed better than CALPUFF with low bias.

7. EVALUATING COMMERCIAL AIR DISPERSION MODELS FOR ODOUR DISPERSION, PART III: USING SWINE ODOUR PLUME MEASUREMENT DATA FROM SASKATCHEWAN

7.1 Introduction

We evaluated four air dispersion models in the application of agricultural odour prediction, e.g. ISCST3, AUSPLUME, CALPUFF and INPUFF2. The simulated odour intensities were compared with the field measured odour intensities in southern Manitoba. We found that the four models performed similarly with relatively low agreements and the scaling factors were not very useful for the results improvement. However, the monitoring distance was within 1000 m from the swine production sites, which was less than recommended setback distances by Canadian Prairie Provinces.

The objective of this study was to evaluate CALPUFF and INPUFF2 models at distances ranging from 0.2 to 6.4 km from the swine farms by comparing the model predicted odour intensity with field measured odour intensities obtained by trained odour assessors.

7.2 Materials and Methods

7.2.1 Odour plume measurement data

7.2.1.1 Site Description and Odour Emission Rates

Three different swine operation sites located close to each other were selected in eastern Saskatchewan, Canada. These three farms included the farrowing (5,000 sows, 3 barns, one 2-cell earthen manure storage basin (EMS)), nursery (19,200 head, 4 barns, one 2-cell EMS), and finishing (11,550 head, 1 barn, one 2-cell EMS) sites (Guo et al., 2005). Figure 7.1 outlined the layout of the study area. The study area was a rural crop land with flat terrain and free of obstacles. Odour emissions from all types of sources on the three sites were measured monthly from May to October 2003. Table 1 gives the monthly odour emission rates of the barns and the average emission rates of the EMSs.

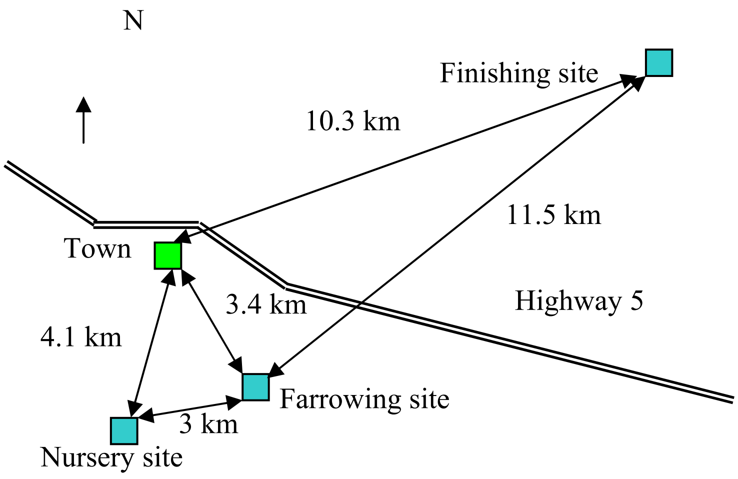


Figure 7.1 Outline of the odour monitoring area (Guo et al., 2005)

Table 7.1 Odour concentration and emissions from barns and manure storage (Guo et al., 2005)

Date	Total building odour emission (OU/s)			Building odour emission rate (OU/m^2-s)			EMS average odour emission rate during 05-10, 2003 (OU/s/m^2)					
	Farrow	Nursery	Finishing	Farrow	Nursery	Finishing	Farrow cell 1	Farrow cell 2	Nursery cell 1	Nursery cell 2	Finishing cell 1	Finishing cell 2
21/05/2003	60113	155384	967556	12	20	101	6	35	24	26	48	31
24/06/2003	124689	427697	266844	24	55	28						
7/14-22/2003	270095	352493	424428	52	45	44	Average EMS total odour emission (OU/s) during 05-10, 2003					
19/08/2003	68512	71896	252158	13	9	26	16122	164434	134804	252811	270537	302732
24/09/2003	238142	146844	619044	46	19	65						
20/10/2003	210612	179111	219693	41	23	23						

7.2.1.2 Downwind Odour Intensity Monitoring

Unlike the previous downwind odour plume measurement using a group of 5 to 15 odour assessors that trying to measure the odour plume at different distances at the same time, this study used two odour assessors (one male and one female) selected from outside of the study area. They were trained with 5-point n-butanol reference intensity scale to estimate the odour intensity in the field (Procedure B, Static-Scale Method, ASTM E544-99 1999).

The two assessors monitored odours around the three swine sites for six months, from May to October 2003, at a total of 119 designated locations. These locations were placed 0.2 to 6.4 km from the closest swine site. For each of the 8 wind directions, the assessors were given a specific route to travel in order to cover all downwind locations (Guo et al., 2005). For each trip, the odour assessor estimated the wind direction first and then traveled through the area on the particular route corresponding to the wind direction (Guo et al., 2005). There was only one odour intensity record in the corresponding location during one trip. At each location, the assessor took measurements for 30 s by sniffing once every 10 s, and recorded the maximum odour intensity and corresponding hedonic tone. The time intervals between measurements at adjacent locations were between 2 to 15 min depending on the distance between the two adjacent locations and they usually worked separately in the early morning, early evening, and occasionally in the afternoon. Each trip took 2 to 3 hours. They worked together for a total of 12 days between June and September in order to compare their readings. The monitoring methods can be found in Guo et al. (2005) for further detail descriptions.

A weather station was placed 2 m above the ground close to the finishing site to collect weather information including solar radiation, temperature, relative humidity, and wind speed and direction during the odour monitoring period.

7.2.2 Model Configurations

CALPUFF and INPUFF2 were used in this study same reasons as described in chapter 6. To run the models, the barn and the manure storages were all considered as area sources for CALPUFF, but point sources for INPUFF2 because of the source type limitation. CALPUFF used hourly average meteorological data and predicts hourly average simulation values. INPUFF2 can use any time periods ranging from seconds to hours for simulation. In this study, 10 minutes average meteorological data were used by INPUFF2 to obtained 10 min average predicted odour concentrations for each run.

7.2.3 Relationship between Odour Concentration and Intensity

In this study, the relationship between odour concentration and intensity using the odour samples taken by this study was not measured at the olfactormetry lab, University of Alberta. The conversion equation 3.6 for swine odour from the University of Minnesota was applied to these study results. There are mainly three reasons for the selection of this equation. Firstly, the same intensity scale was used by this study and the University of Minnesota research (Guo et al., 2001). Secondly, in the previous study, this conversion equation performed better than that from University of Manitoba and University of Alberta (Chapter 4). Thirdly, 124 odour samples were collected from 60 swine buildings and 66 swine manure storage facilities in Minnesota during

1998 and 1999 to determine the conversion equation which make this equation better represent the relationship between odour concentration and intensity.

Table 7.2 Odour intensity reference scale (Guo et al., 2001)

Intensity level	Annoyance	N-butanol solution (ppm)	Odour concentration （OU/m^3）	Odour concentration range （OU/m^3）
0	No odour	0	0	<5
1	Very Faint	250	25	5~42
2	Faint	750	72	42~124
3	Moderate	2250	212	124~364
4	Strong	6750	624	364~1070
5	Very Strong	20250	1834	>1070

7.2.4 Comparisons between Model Predictions and Field Measurements

A total of 33 trips or measurement sessions were selected, each session lasted 1 to 4 hours. The measurements were conducted during non-manure application times, eliminating odour emissions from crop lands with manure application. For CALPUFF model, hourly average meteorological data was used to get the hourly odour concentration predictions. Because all the locations were input into the model, the predicted odour concentration for every location was obtained. Then the odour concentration was converted to odour intensity using equation 3.6, then for all the measured locations during that hour the modeled odour intensities for those locations were compared with the measured odour intensities by the odour assessors and the agreement was determined. For INPUFF2, 10 min average meteorological data were used for the whole session, therefore, average odour concentrations of every 10 min at all locations were predicted for the whole measurement session. The predicted odour concentrations were then converted to odour intensities according to equation 3.6. Finally, the measured odour intensities at all measured locations during that session were compared with the model predicted odour intensities at the detection times.

7.3 Results and Discussions

7.3.1 Agreement Analysis

The field odour measurement locations were 0.2 to 6.4 km from the closest swine farm and we categorized them into the 4 ranges of distances, ≤500 m, 500 to 1000 m, 1000 m to 3000 m, and over 3000 m. A total of 33 measurement sessions (or measurement trips) were used in this study. There were a total of 837 pairs of measured and modeled data points used in the data analysis, of which 254 measurements had odours detected.

Table 7.3 summarizes the overall agreements between the modeled and measured odour intensities for the two models. If all measurements were considered, these two models both gave satisfactory agreements from 52% to 81% for distance over 1 km because most of the field measurements and model predictions were close to intensity level zero. For the distance from 500 to 1000 m, the agreements were lower with 37% and 45% for CALPUFF and INPUFF2 respectively, which were lower than the range from 70% to 76% obtained in Chapter 5 for Manitoba's odour assessors' odour plume measurement data. When the distance was over than 1 km, there were 91% data points fell into this range and the models had good performance for over 1 km. Comparing these two models, INPUFF2 performed better (69%) than CALPUFF (59%) for all distances.

However, if we only consider the measurements with odours detected, i.e. excluding all the measurements with zero odour intensity, then the agreements of the modeled and measured values reduced as given in Table 7.4. CALPUFF performed better than INPUFF2 for all different range of distances. INPUFF2 had no agreement for distance over 3000 m. From the detail agreements given in Appendix C, most of the models predictions by CALPUFF were lower than the measured values, and for INPUFF2, all the measurements were higher than the models ones.

Table 7.3 Agreements between CALPUFF and INPUFF2 models predictions and field measurements for all field measurements including intensity level 0

Downwind distance	Agreement (%)		% data points of each distance range
	CALPUFF	INPUFF2	
500 m	35	44	4
1000 m	38	45	5
500 to 1000 m	37	45	9
1000 to 3000 m	52	63	50
>3000 m	72	81	41
Overall	59	69	100

Table 7.4 Agreements between CALPUFF and INPUFF2 models predictions and field measurements for all field measurements excluding intensity level 0

Downwind distance	Agreement (%)		% data points of each distance range
	CALPUFF	INPUFF2	
500 m	19	10	8
1000 m	9	0	9
500 to 1000 m	14	5	17
1000 to 3000 m	14	3	57
>3000 m	6	0	26
Overall	12	2	100

7.3.2 Scaling Factors Analysis

Since the model predictions were lower than the measured ones, so scaling factors should be used to improve the agreements. Barns and manure storages may have different scaling factors as suggested by Zhu et al. (2000). Table 7.5 showed the obtained scaling factors for this part. The scaling factors for INPUFF2 (28.7 for barn and 30.4 for the manure storage) were higher than those of CALPUFF (8.3 for barn and 11.4 for the manure storage) because the INPUFF2's predictions were much lower than CALPUFF's predictions as shown in Appendix C. The main reason for the difference is that CALPUFF used hourly meteorological data to predict hourly odour concentration so it allowed odour to travel farther distance along the downwind direction; while the INPUFF2 used 10 min meteorological data to predict 10 min odour concentration and the wind direction shift from one 10 min period to another had an dilution effect for odour plume and might not allow the odour travel as far and result in lower odour concentration as compared with predictions by CALPUFF. This result is also consistent with the results reported in Chapter 4, i.e. compared with other models, INPUFF2 always gave the lowest predicted values under different weather conditions. After using the scaling factors, the agreement of the modeled predictions and the field measurements were increased by 4% to 24% (Table 7.6). The modified agreements for measurements excluding intensity level 0 were increased from 12% to 28% for CALPUFF and 2% to 17% for and INPUFF2. Therefore, the scaling factors were useful to improve the model performance in this study. Figures 7.2 and 7.3 showed the comparison of measured and modeled odour intensities for one session taken during 16:48 to 20:09, on May 15th. Location 96 and 27 were 3 km away from the closet farm while location 30 was 0.15 km from the farm. In the figures, the models (as shown in line) gave continuous odour concentration changes during the session while there were odours measured at three locations (indicated as points) during the session in the field. The figures also indicted that the model predictions were basically lower than the measured ones.

Table 7.5 Scaling factors for CALPUFF and INPUFF2

Model	Scale Factor	
	Barn	Manure storage
CALPUFF	8.3	11.4
INPUFF2	28.7	30.4

Table 7.6 Agreements of the original results (unadjusted) and after using scale factor (without considering intensity 0)

Distances	Agreement (%)			
	CALPUFF		INPUFF2	
	Original	Modified	Original	Modified
500 m	19	38	10	14
1000 m	9	18	0	14
500 to 1000 m	14	28	5	14
1000 m to 3000 m	14	28	3	18
>3000 m	6	30	0	15
Overall	12	28	2	17

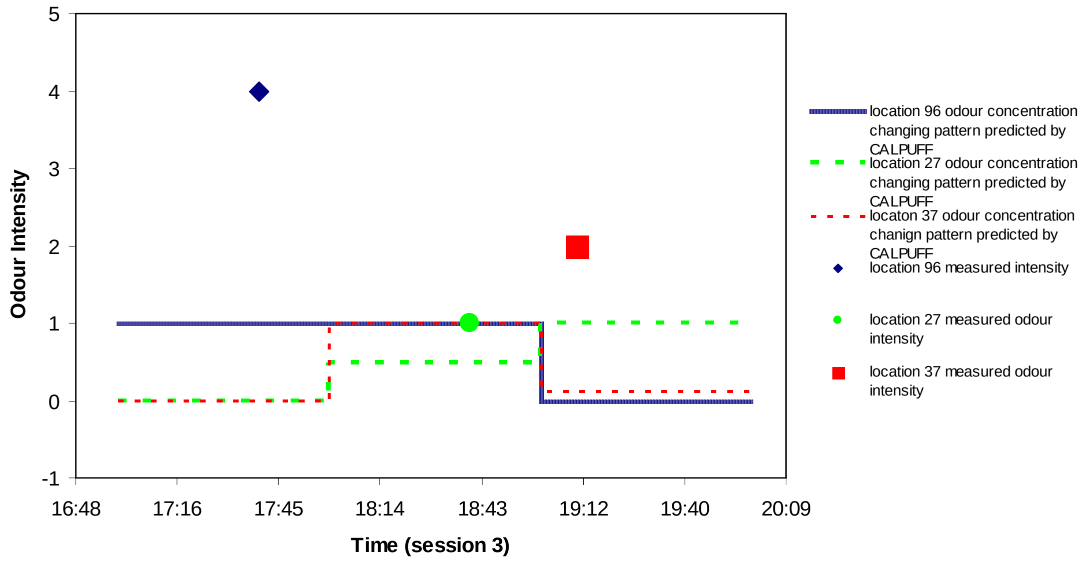


Figure 7.2 Measured odour intensities vs. predicted ones by CALPUFF

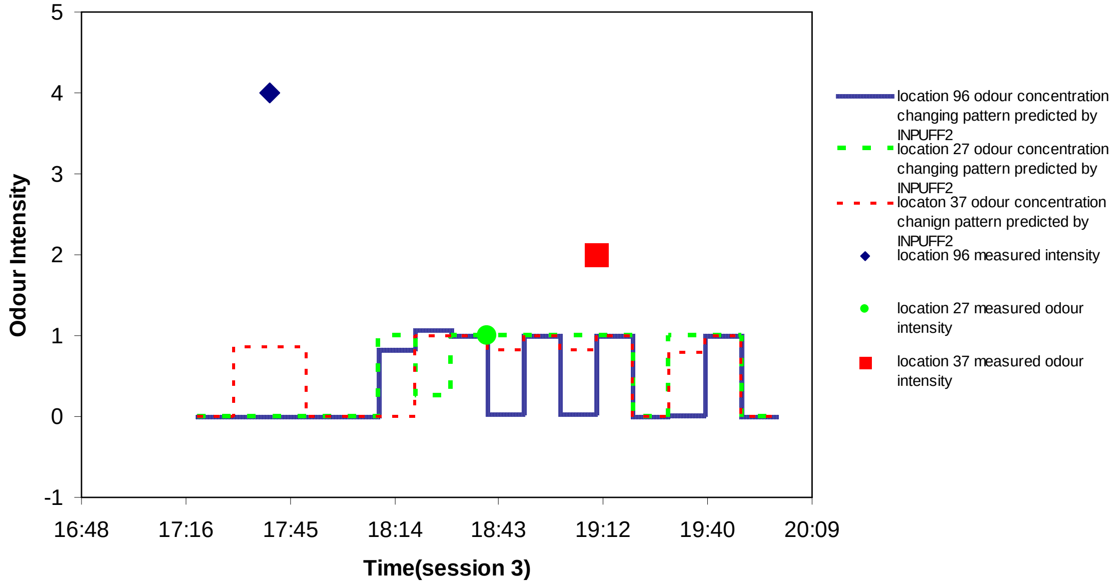


Figure 7.3 Measured odour intensities vs. predicted ones by INPUFF2

7.4 Conclusions

Considering all the measurements taken and using the odour intensity and concentration conversion equation generated by University of Minnesota, the predictions of the two models, CALPUFF and INPUFF2, achieved 52% to 81% of agreement with the measured odour intensities for distances over 1000 m. For the distance from 500 to 1000 m, the agreements were lower than that obtained using the plume measurements data from University of Manitoba. INPUFF2 performed better than CALPUFF. However, if the measurements with intensity zero (no odour) were excluded, the agreement was reduced to 2 to 12% for all distances and 5 to 14% for distance of 500 to 1000 m.

Scaling factors were generated to adjust the modeled results in order to improve the agreements of modeled and measured odour intensities because most of the models predictions were lower than the measured odour intensity. The scaling factors for INPUFF2 (28.7 for barn and 30.4 for the manure storage) were higher than those of CALPUFF (8.3 for barn and 11.4 for the manure storage). After the scaling factors were applied, the agreement achieved 28% for CALPUFF and 17% for INPUFF2.

8. APPLICATION OF AIR DISPERSION MODELS TO ESTABLISH SETBACK DISTANCES FROM CONFINED FARMING OPERATIONS

8.1 Introduction

Unlike empirical guidelines used to estimate the setback distance, air dispersion models can be used to calculate the setback distances to achieve certain acceptable odour occurrence levels. The objective of this study was to use the selected model CALPUFF to simulate odour plumes under historical weather conditions on a selected location using historical weather data for typical sized swine operations in Yorkton, Saskatchewan where the odour sniffer measurements were conducted. After the simulation, the predicted odour concentration contour results will be compared with the recommended setback distances in Saskatchewan to find out the equivalent odour concentration for various setback requirements.

8.2 Materials and methods

The study area was in the Yorkton, Saskatchewan and Figure 7.1 showed the simple layout the three swine operations, which were of the typical sizes for large swine production farms in Canadian Prairies. To obtain the annual average odour concentration contour in the nearby area of the swine sites, 10 years continuous meteorological data, i.e. 1993-2002 hourly meteorological data from Yorkton, Saskatchewan, Canada were used. To obtain the average odour concentration contour during the high odour occurrence season, i.e. warm season, 1993 to 2002 warm seasons (May to October) data were used. For the warm season, because the dates were not continuous, the odour dispersion was simulated year by year and the odour concentrations over the 10 warm seasons were then averaged as 10-year warm season average odour concentrations. Due to none odour emissions from manure storages in cold season (January to April, November, and December), we conducted the 10 years continuous model simulation by using different emission rates for cold season and warm season, as given in Table 8.1. The geometric mean emission rates in warm season and cold season were used as the monthly emission rates during the periods of these two seasons so that they could represent general emission rates for these two seasons.

According to the results from Chapter 5 to 7, INPUFF2 generally had better performance than the other models. However, this model is not easy to use in annual odour concentration predictions since INPUFF2 only accepts 144 time periods in one run, the one year hourly meteorological data had to be divided into numerous periods of 144 hr each. If 10 years meteorological data were used for this model, it would take a long time to finish the simulation. CALPUFF is also a preferred model as recommended by US EPA (1995). Therefore, we used CALPUFF to conduct the odour dispersion simulation. As showed in Figure 7.1, the study area was very big and the number of receptors for the models is limited, so we conducted one preliminary study to determine the receptor grid spacing. Uniform spacing of 200 m receptor grid was found as the shortest grid in order to allow the model simulation for all three sites to be conducted at the same time and cover the odour dispersion areas to odour concentrations of as low as 1 OU. Therefore, uniform grids of receptors with 200 m spacing were used for the model simulation.

Table 8.1 Odour concentrations and emission rates from barns and manure storages

Odour source		Odour emission (OU/s)		Odour emission rate (OU/s-m^2)	
		Warm season geometric mean	Cold season geometric mean	Warm season geometric mean	Cold season geometric mean
Farrowing	Barn	138165	149830	26.7	28.9
	Cell 1	16122	0	5.5	0
	Cell 2	164434	0	34.5	0
Nursery	Barn	188102	267188	24.0	34.1
	Cell 1	134804	0	24.0	0
	Cell 2	252810	0	25.8	0
Finishing	Barn	394297	513891	41.3	53.8
	Cell 1	270537	0	48.1	0
	Cell 2	302732	0	30.9	0

8.3 Results and Discussions

The contour maps of 10 years warm season and annual average odour concentrations were shown in Figures 8.1 and 8.2. The odour isopleths for various odour concentrations varies in all directions, with the maximum distances occurring leeward of the prevailing winds in the NNW, WNW and SSE areas. Guo et al. (2005) studied odour occurrence in this area and found the locations with high odour events were mostly downwind of the prevailing winds from the farms. The maximum odour travel distances can be used for the determination of the maximum setback distances for the corresponding farms. The minimum distances were always in the upwind from the farm sites and they can be used for the minimum setback distance determination. Comparing these two figures, the contour shapes for three sites were similar but the odour affected areas during the warm season were bigger than the annual average odour concentration contour areas. The differences indicated that the high odour concentrations mainly occurred in the warm season. The reports by the environmental agencies on the odour complaints by people living in the vicinity of animal producing farms showed similar seasonal patterns, concentrated during the warm season (Strauss et al., 1986; Schiffman, 1994; Lohr, 1996).

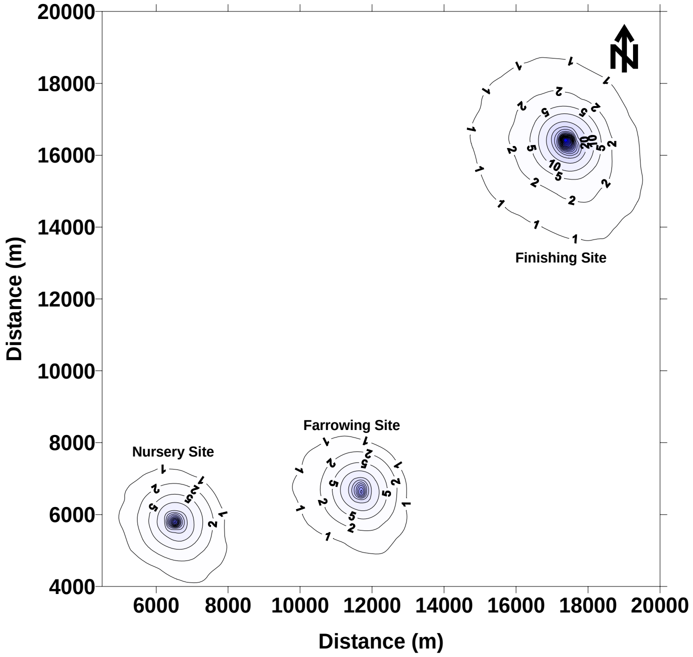


Figure 8.1 Ten-year warm season odour concentration (OU/m^3) contour map for three farm sites

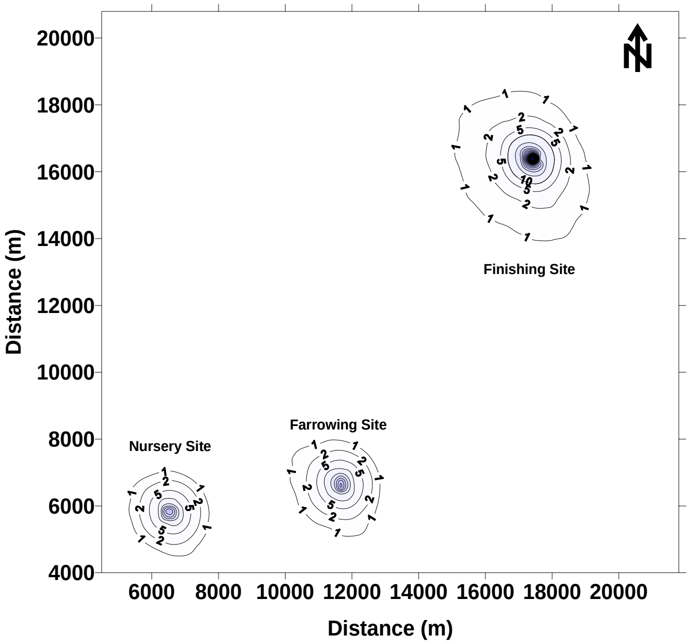


Figure 8.2 Ten-years average annual odour concentration (OU/m^3) contour map for three farm sites

The maximum and minimum downwind distances for 1, 2, 5, and 10 OU/m^3 during 10-year warm seasons are presented in Tables 8.2 to 8.4 for different farm sites. If 10-year warm season average odour concentrations from 1 to 10 OU/m^3 are used as setback criteria, the maximum setback distance for Nursery farm and Farrowing site were similar, which will be in the range of 0.5 to 1.9 km, which falls in the recommended maximum setback distances 3.2 km by Saskatchewan (Saskatchewan Agriculture and Food, 1999). The predicted maximum setback distance for Finishing site ranges from 0.9 to 2.9 km which is higher than the Nursery and Farrowing sites but they were still lower than the maximum recommended setback of 3.2 km. Besides the maximum dispersion distances, we also calculated the minimum dispersion distances from the emission sources. Near the Nursery and Farrowing farms, the minimum distances were in the range of 0.4 to 1.3 km while 0.7 to 1.9 km for the Finishing site. For the odour level of 1 OU/m^3, the predicted minimum distances were higher than the recommended minimum setback distance 1.2 km.

If we consider 10-year average odour concentration as setback criteria, the maximum and minimum downwind distances for 1, 2, 5, and 10 OU/m^3 were lower than the warm season values as shown in Tables 8.5 to 8.7. The maximum downwind travel distances for the three farm sites predicted by CALPUFF were all fell into the recommended maximum values 3.2 km for Saskatchewan. Tables 8.5 and 8.6 showed the maximum setback distances for Nursery farm and Farrowing site, they had the similar ranges of from 0.4 to 1.7 km while it was from 0.7 to 2.5 km for Finishing site. For the determination of minimum setback distance, near the Nursery and Farrowing barn, the minimum distances were in the range of from 0.3 to 1.2 km and from 0.4 to 1.2 km, respectively. The Finishing site had the value ranging from 0.6 to 1.6 km. Compared with the recommend minimum values 1.2 km, the distance predicted by the model for Nursery and Farrowing farm, all the values were within the range. However, for the odour level 1 OU/m^3, the predicted minimum distances for Finishing site were higher than the recommended minimum setback distance 1.2 km. Except odour level 1 OU/m^3, the other dispersion distances corresponding to 2 to 10 OU/m^3 were all lower than the recommend minimum distances.

Comparing the 10 years average odour concentrations with the results obtained using warm season weather data, odour can travel farther under warm season weather condition if using the same odour concentration criterion. For example, for Finishing site, odour can travel up to 2.9 km under warm season as compared to 2.5 km for annual average for the odour to be diluted to 1 OU/m^3. The differences in odour travel distances under these two weather conditions mainly caused by: a) the lower emission rates from the farms because the manure storage had no emission in cold season, and b) in the warm season, the higher temperature caused higher odour concentrations as found in Chapter 4.

To summarize, the predicted setbacks by CALPUFF using the odour criteria of 1 to 10 OU/m^3 were always lower than the recommended maximum setback distances in Saskatchewan. As discussed previously, the air dispersion models used for odour dispersion are designed for gas dispersion modeling instead of odour dispersion modeling; scaling factors may be needed to improve the model predictions as found in the previous chapters. However, if the scaling factors obtained in Chapter 7 were used (8.3 for barns and 11.4 for EMSs), the predicted setbacks would be increased by 10 times for the same odour concentration criteria, or the acceptable odour concentration criteria would be allowed to be increased by close to 10 times, which would bring the acceptable odour concentration criteria closer to what were used by OFFSET model (75 OU) and Australian (11 OU). Further work is needed to determine the acceptable odour criteria.

Table 8.2 Maximum and minimum distances in the vicinity of Nursery site for different odour levels in warm season and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for Nursery site (19,200 head, 960 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan (km)
1	1.8	SSE	1.3	NE	Min.: 1.2
2	1.1	SSE	1.0	NE	
5	0.8	SSE	0.7	NE	
10	0.5	SSE	0.4	NE	Max.: 3.2

Table 8.3 Maximum and minimum distances in the vicinity of Farrowing site for different odour levels in warm season and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for Farrowing site (5000 head, 1250 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan (km)
1.0	1.9	SSE	1.3	NE	Min.: 1.2
2.0	1.3	SSE	1.0	NE	
5.0	0.8	SSE	0.7	NE	
10.0	0.5	SSE	0.5	NE	Max.: 3.2

Table 8.4 Maximum and minimum distances within the vicinity of Finishing site for different odour levels in warm season and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for Finishing site(11550 head, 1925 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan (km)
1	2.9	SSE	1.9	NE	Min.: 1.2
2	1.7	SSE	1.2	NE	
5	1.1	SSE	0.9	NE	
10	0.9	SSE	0.7	NE	Max.: 3.2

Table 8.5 Maximum and minimum distances in the vicinity of Nursery site for different odour levels using ten–year average odour concentrations and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for nursery site (19200 head, 960 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan
1	1.4	SSE	1.2	NE	Min.: 1.2
2	1.0	SSE	0.9	NE	
5	0.7	SSE	0.5	NE	
10	0.4	SSE	0.3	NE	Max.: 3.2

Table 8.6 Maximum & minimum distances in the vicinity of Farrowing site for different odour levels using ten–year average odour concentrations and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for Farrowing site (5000 head, 1250 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan (km)
1	1.7	SSE	1.2	NE	Min.: 1.2
2	1.1	SSE	0.9	NE	
5	0.8	SSE	0.7	NE	
10	0.5	SSE	0.4	NE	Max.: 3.2

Table 8.7 Maximum and minimum distances in the vicinity of Finishing site for different odour levels using ten–year average odour concentrations and recommended setback distance range in Saskatchewan

Odour level (OU/m^3)	CALPUFF for Finishing site(11550 head, 1925 animal unit)				
	Maximum distance (km)	Wind direction	Minimum distance (km)	Wind direction	Recommended setback distance in Saskatchewan (km)
1	2.5	SSE	1.6	NE	Min.: 1.2
2	1.5	SSE	1.1	NE	
5	1.0	SSE	0.9	NE	
10	0.7	SSE	0.6	NE	Max.: 3.2

8.4 Conclusions

1. In warm season, the maximum distances for Nursery and Farrowing farms for odour level, 1, 2, 5, and 10 OU/m^3 ranged from 0.5 to 1.9 km; for Finishing farm, the values were in the range of from 0.9 to 2.9 km, which were higher than the other farms. These predictions were all within the recommended maximum setback distance of 3.2 km in Saskatchewan. The minimum distances for Nursery and Farrowing farms were ranging from 0.4 to 1.3 km while that was 0.7 to 1.9 km for the Finishing farm. Except of the odour level 1 OU/m^3, the minimum dispersion distance for other odour levels were all lower than the recommend setback distance of 1.2 km.
2. In the average odour concentrations during the whole 10 years, the maximum distances for Nursery and Farrowing farms for odour level, 1, 2, 5, and 10 OU/m^3 ranged from 0.4 to 1.7 km, and for Finishing farm, the values were in the range of from 0.7 to 2.5 km, which were higher than the other farms. These predictions were also all within the recommended maximum setback distance 3.2 km. The minimum distances for Nursery and Farrowing farms were ranging from 0.3 to 1.2 km while it ranged from 0.6 to 1.96 km for the Finishing farm. For Nursery and Farrowing farms, all the predicted dispersion distances were within 1.2 km. For Finishing farm, except of the odour level 1 OU/m^3, the minimum dispersion distances for other odour level were all lower than the recommend setback distance 1.2 km.
3. The predicted maximum and minimum odour travel distances under warm season were all higher than that obtained by using 10-year annual meteorological data. The higher emission rates from the farms and higher atmospheric temperature in the warm season were the main reasons that caused the difference.
4. Further research is needed to include scaling factors in the modeling and to determine the acceptable odour criteria.

9. SUMMARY

Using air dispersion models to calculate downwind livestock odour concentrations in the vicinity of livestock operations is a practical approach to determine the setback distances between odour sources and their neighbours in order to reduce the odour nuisance. Most of the air dispersion models were originally designed for industrial applications. Many odour researchers have validated some of the air dispersion models to predict the agricultural odour dispersion. These air dispersion models need to be evaluated against field odour measurement data when applied in agricultural odour dispersion simulation, however limited work has been done. As indicated in Chapter 1, the lack of experimental data to quantitatively examine the performance of air dispersion models has become the major obstacle in using these models to predict odours from agricultural sources. In recent years, extensive odour plume measurements were conducted in the U.S.A. and Canada, which made it possible to evaluate the air dispersion models for odour dispersion simulation.

The research described in this thesis is focused on evaluating the selected air dispersion models, i.e., ISCST3, AUSPLUME, CALPUFF and INPUFF2 for livestock odour dispersion by comparing to the field odour nasal sniffers' measurements and comparing the predictions among these models. The field data were obtained from University of Manitoba, University of Minnesota, and University of Saskatchewan described in Chapter 2.

Before model validation, a sensitivity analysis was conducted (Chapter 4) to understand how the model climatic parameters affect the odour dispersion for all four models. Five parameters, i.e. mixing height, ambient temperature, atmospheric stability, wind speed, and wind direction, were analysed under steady state weather conditions based on one selected livestock facility in Saskatchewan. It was found that mixing height has no effect on the odour dispersion for all four air dispersion models. The ambient temperature had significant influences on the odour travel distance as predicted by INPUFF2 but its effect on the other models was moderate. High ambient temperature favours odour travel. The effect of the ambient temperature gradually reduces with the increase of distance and disappeared at 1 km except INPUFF2. Atmospheric stability has great impact on odour travel distance and all models show similar sensitivity to the changing stability. Stable weather favours odour travel. Wind direction had great impact on odour travel distances and odour concentrations near the swine farms. In the other word, the source orientation's effect on the odour dispersion is considerable especially at close distance downwind. Comparing the model predictions under all steady state weather conditions, ISCST3 and CALPUFF give similar results (within 24.8%) while AUSPLUME and INPUFF2's predictions are much lower than that of ISCST3 (up to 45.3% beyond 0.5 km) for odour concentration and the maximum downwind distance from the source. The differences between the model predictions generally decreased with the increase of instability and wind speed, and generally stabilized beyond 1 km from the source. Using the annual hourly meteorological data in 2003 for Yorkton, Saskatchewan, the models were also used to calculate annual average odour concentrations in the nearby area in order to evaluate their performance under variable weather conditions. CALPUFF predicted the greatest distances for odour concentrations from 1 to 10 OU/m^3 while INPUFF2 predicted the shortest distances. Variable weather conditions make AUSPLUME and CALPUFF produce higher predictions than ISCST3, which was different from the results obtained under steady state weather conditions. When setting odour criterion for setback distance, it is recommended that if steady state weather data are used, the odour concentration should be allowed to set high.

After sensitivity analysis, three sets of field odour intensity measurements data obtained by nasal rangers were used to validate the selected air dispersion models in Chapter 5, 6 and 7. In Chapter 5, the selected four models, i.e. ISCST3, AUSPLUME, CALPUFF, and INPUFF2, were evaluated by comparing the model predictions with the plume measurement data from University of Manitoba. Considering all the measurements taken and using the odour intensity and concentration conversion equation generated by University of Manitoba, University of Alberta, and University of Minnesota, the predictions of the four models achieved similar agreements with the measured odour intensities for all distances. INPUFF2 performed the best. However, if we only considered the measurements with odours detected, i.e. excluding all the measurement with zero intensity, and comparing the agreements using different conversion equations, the agreements using the equations from University of Alberta and University of Minnesota were still similar and University of Manitoba's conversion equation performed better in high level odour intensity predictions than the other two. Using ASTM Standard Guide for air dispersion model evaluation with the application of the three conversion equation from all models bias fell into the acceptable value range. Considering the overall performance of the four models, no model showed obvious better performance than the others. The odour intensity and concentration conversion equation is very important to ensure the accuracy of the comparison of the modeled and measured odour intensities. The effectiveness of improving model performance using scaling factors needed to be further examined because it did not significantly improve the model performance in this part.

To further examine the effect of the scaling factor, we rechecked the previous research results from the University of Minnesota using odour plume measurement data from Minnesota in Chapter 6. In this part, only CALPUFF and INPUFF2 were used. The scaling factors were found essential to adjust the model predictions close to the measured values. The main reason caused the different effectiveness of scaling factors between University of Manitoba data and University of Minnesota data might be the lower total odour emission rate in Minnesota. INPUFF2 had better performance than CALPUFF for all field measurements and without considering the odour intensity level 0 which was consistent with the results of Chapter5. However, considering only measurements with odours detected, then CALPUFF performed better than INPUFF2. When using the ASTM Standard to evaluate the models' performance, INPUFF2 performed better than CALPUFF with very low bias.

The monitoring distances in Chapter 5 and 6 were within 1000 m from the swine production sites, which was less than recommended setback distances by Canadian Prairie provinces. Therefore, CALPUFF and INPUFF2 models were evaluated in Chapter 7 at distances from 0.2 to 6.4 km from the closest swine site by comparing the model predicted odour intensity with field odour intensities measured by the trained odour assessors in Saskatchewan. Considering all the measurements taken and using the odour intensity and concentration conversion equation generated by University of Minnesota, the predictions of the two models, CALPUFF and INPUFF2, achieved 52% to 81% of agreement with the measured odour intensities for distances over 1000 m. For the distances from 500 to 1000 m, the agreements were lower than that obtained using the plume measurements data from University of Manitoba. INPUFF2 performed better than CALPUFF. However, if the measurements with intensity zero (no odour) were excluded, the agreement was reduced because most of the model predictions were lower than field measurement data. Scaling factors were generated to adjust the modeled results and improve the agreements of modeled and measured odour intensities. The scaling factors for INPUFF2 (28.7 for barn and 30.4 for the manure storage) were higher than that of CALPUFF (8.3 for barn and 11.4 for the manure storage). After the scaling factors were applied, the agreement achieved 28% for CALPUFF and 17% for INPUFF2.

The application of the air dispersion models to predict setback distances that meet various odour criteria are the main purpose of the odour study. CALPUFF was used to calculate odour concentrations in the nearby areas using historical weather conditions on selected locations for typical sized swine operations which located in Yorkton, Saskatchewan where the odour sniffers measurements were conducted as illustrated in Chapter 8. In warm season from May to October, the predicted maximum distances for Nursery, Farrowing, and Finishing farms for odour level, 1, 2, 5, and 10 OU/m^3 were all less than the recommended maximum setback distance of 3.2 km in Saskatchewan. The minimum distances for Nursery and Farrowing farm were lower than that of the Finishing farm. Except of the odour level 1 OU/m^3, the minimum dispersion distance for other odour level for the three farm sites were all lower than the recommend minimum setback distance of 1.2 km. In the whole 10 year weather data, the maximum distances for the three farm sites were all less than 3.2 km. The minimum distances for Nursery and Farrowing farms, all the predicted dispersion distances were within 1.2 km. For Finishing farm, except of the odour level 1 OU/m^3, the minimum dispersion distances for other odour level were all lower than the recommend minimum setback distance of 1.2 km. Comparing the above results under different weather conditions, the predicted maximum and minimum odour dispersion distances under warm season were all higher than that obtained by using 10 year annual meteorological data. The higher emission rates from the farms and high ambient temperature in the warm season were the main reasons for the difference. Further research is needed to include scaling factors in the modeling and to determine the acceptable odour criteria.

In the future, in order to determine proper setback distance, we can have two options with the weather conditions from the sensitivity analysis conclusions. One way is to use the steady state weather conditions and the other is to use the hourly variable meteorological data. The steady state weather considered the worst situations which make the odour travel for long distance, but in the model simulation, the running time needs to be tried so as to make the odour transport the farthest. The variable weather conditions use the regular meteorological data which is easy to obtain and can be input into the models easily. Therefore, the variable weather conditions were recommended to use in the setback distance determination.

The input file for the ISCST3 models makes use of a keyword/parameter approach to specifying the options and input data for running the models. To use ISCST3, the users need to learn how to use the descriptive keywords and parameters that make up the input run-stream file. AUSPLUME is the extension of ISCST3, but it still based on the steady state assumption that the plume travels in a straight line in the uniform flow with homogenous turbulence which can not reflect the real odour transport situations. CALPUFF is the US EPA preferred models and it predicted the highest results with variable meteorological data which can make the predicted setback distance longer than the other three models, so it is suggested to use in the livestock odour dispersion simulation. Because INPUFF2 can take into account short time interval such as 1 s or 1 min, it is also recommended in the application of the setback distance determination, especially for odour plume simulation.

In this thesis, steady state models (Gaussian Plume models, i.e. ISCST3 and AUSPLUME) and non steady state model (Puff models, i.e. CALPUFF and INPUFF2) were applied in the livestock odour dispersion prediction. They were all developed for industrial air pollutant dispersion simulation so when used for odour dispersion simulation all have disadvantages and cannot be directly used for odour dispersion simulation. The main reasons are the different measurement methods for odour concentration than gas concentrations and the instantaneous nature of field odour intensity measurement method. Scaling factors based on the comparison of modeled and measured odour plumes which include the effect of these two factors and the peak to mean ratio caused by wind direction shift should be used to adjust the modeled results. As mentioned in 2.4, the steady state models assumes that the plume centerline travels a straight line to the edge of the modeling area regardless of whether it could physically do so at the given wind speed. Another problem is that the dispersion coefficients are evaluated for time scales of 10 to 60 minutes so that they predict average concentrations for the same time scale. Further more, the wind direction used in the steady state model is constant over one hour. However, the fluctuation of wind direction is great in one hour which causes different odour nuisance level. The non-steady state model (CALPUFF and INPUFF2) can address wind shift more accurately. However, CALPUFF can only use hourly meteorological data which can not satisfy the livestock odour dispersion with short time interval such as 1 second or 1 minute. INPUFF2 used the instantaneous input meteorological data to predict the odour concentration. This advantage makes the results more close to the reality. But the instant meteorological data is difficult or expensive to obtain compared with the regular meteorological data. Therefore, a model that can accurately estimate the odour concentration downwind the livestock operations should be developed which can deal with above model limits.

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11. APPENDIX A: DETAILED AGREEMENT ANALYSIS RESULTS OF THE MODELED AND MEASURED ODOUR INTENSITIES USING UNIVERSITY OF MANITOBA'S PLUME MEASUREMENT DATA

Table A- 1 Total measured and ISCST3 predicted odour intensity data comparison using Equation 3.8

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	29	3	10	0	0	0	0	42	29	69
	1-3	48	29	32	3	0	0	0	112	29	26
	4	16	7	16	2	0	0	0	41	16	39
	5	15	8	4	0	0	0	0	27	0	0
	6	6	5	3	0	0	0	0	14	0	0
	7	1	1	3	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	45	23
	0-8								242	74	31
500 m	0	141	30	2	0	0	0	0	173	141	82
	1-3	95	20	2	0	0	0	0	117	20	17
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	20	17
	0-8								291	161	55
1000 m	0	241	20	0	0	0	0	0	261	241	92
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	241	85
Total	1-8								341	65	19
Total	0-8								817	476	58

Table A- 2 Total measured and AUSPLUME predicted odour intensity data comparison using Equation 3.8

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	25	4	12	1	0	0	0	42	25	60
	1-3	33	53	25	1	0	0	0	112	53	47
	4	10	25	6	0	0	0	0	41	6	15
	5	11	13	3	0	0	0	0	27	0	0
	6	4	8	2	0	0	0	0	14	0	0
	7	2	1	2	0	0	0	0	5	0	0
	8	1	0	0	0	0	0	0	1	0	0
	1-8								200	59	30
	0-8								242	84	35
500 m	0	123	40	7	3	0	0	0	173	123	71
	1-3	89	23	3	2	0	0	0	117	23	20
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	23	19
	0-8								291	146	50
1000 m	0	227	21	9	4	0	0	0	261	227	87
	1-3	20	2	1	0	0	0	0	23	2	9
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	2	9
	0-8								284	229	81
Total	1-8								341	84	25
Total	0-8								817	459	56

Table A- 3 Total measured and CALPUFF predicted odour intensity data comparison using Equation 3.8

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	23	7	12	0	0	0	0	42	23	55
	1-3	41	32	37	2	0	0	0	112	32	29
	4	13	10	17	1	0	0	0	41	17	41
	5	12	10	5	0	0	0	0	27	0	0
	6	4	4	5	1	0	0	0	14	0	0
	7	1	1	3	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	49	25
	0-8								242	72	30
500 m	0	133	35	4	1	0	0	0	173	133	77
	1-3	88	27	2	0	0	0	0	117	27	23
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	27	23
	0-8								291	160	55
1000 m	0	239	20	2	0	0	0	0	261	239	92
	1-3	22	1	0	0	0	0	0	23	1	4
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	1	4
	0-8								284	240	85
Total	1-8								341	77	23
Total	0-8								817	472	58

Table A- 4 Total measured and INPUFF2 predicted odour intensity data comparison using Equation 3.8

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	912	98	44	13	0	0	0	1067	912	85
	1-3	1392	427	223	31	0	0	0	2073	427	21
	4	454	149	70	8	0	0	0	681	70	10
	5	436	118	39	6	0	0	0	599	6	1
	6	268	102	46	4	0	0	0	420	0	0
	7	101	45	35	14	0	0	0	195	0	0
	8	26	6	3	1	0	0	0	36	0	0
	1-8								4004	503	13
	0-8								5071	1415	28
500 m	0	3613	573	33	1	0	0	0	4220	3613	86
	1-3	1678	348	35	0	0	0	0	2061	348	17
	4	78	25	1	0	0	0	0	104	1	1
	5	11	12	0	0	0	0	0	23	0	0
	6	4	4	0	0	0	0	0	8	0	0
	7	0	3	0	0	0	0	0	3	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								2199	349	0
	0-8								6419	3962	62
1000 m	0	5277	410	5	0	0	0	0	5692	5277	93
	1-3	427	26	0	0	0	0	0	453	26	6
	4	2	0	0	0	0	0	0	2	0	0
	5	2	0	0	0	0	0	0	2	0	0
	6	1	0	0	0	0	0	0	1	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								458	26	6
	0-8								6150	5303	86
Total	1-8								6661	878	13
Total	0-8								17640	10680	61

Table A- 5 Total of measured and ISCST3 predicted odour intensity data comparison using Equation 3.9

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	30	2	6	4	0	0	0	42	30	71
	1-3	51	30	22	8	1	0	0	112	30	27
	4	16	17	5	3	0	0	0	41	5	12
	5	16	9	1	1	0	0	0	27	1	4
	6	6	5	3	0	0	0	0	14	0	0
	7	1	2	2	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	36	18
	0-8								242	66	27
500 m	0	145	28	0	0	0	0	0	173	145	84
	1-3	102	14	1	0	0	0	0	131	14	11
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								132	14	11
	0-8								305	159	52
1000 m	0	249	12	0	0	0	0	0	261	249	95
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	249	88
Total	1-8								341	50	15
Total	0-8								817	474	58

Table A- 6 Total of measured and AUSPLUME predicted odour intensity data comparison using Equation 3.9

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	25	9	7	1	0	0	0	42	25	60
	1-3	39	60	10	3	0	0	0	112	60	54
	4	11	29	1	0	0	0	0	41	1	2
	5	13	14	0	0	0	0	0	27	0	0
	6	5	8	1	0	0	0	0	14	0	0
	7	2	3	0	0	0	0	0	5	0	0
	8	1	0	0	0	0	0	0	1	0	0
	1-8								200	61	31
	0-8								242	86	36
500 m	0	135	32	3	3	0	0	0	173	135	78
	1-3	98	15	2	2	0	0	0	117	15	13
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	15	13
	0-8								291	150	52
1000 m	0	230	22	5	4	0	0	0	261	230	88
	1-3	20	3	0	0	0	0	0	23	3	13
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	3	13
	0-8								284	233	82
Total	1-8								341	79	23
Total	0-8								817	469	57

Table A- 7 Total of measured and CALPUFF predicted odour intensity data comparison using Equation 3.9

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	24	8	9	1	0	0	0	42	24	57
	1-3	47	37	17	11	0	0	0	112	37	33
	4	13	20	6	2	0	0	0	41	6	15
	5	12	13	2	0	0	0	0	27	0	0
	6	4	7	1	2	0	0	0	14	0	0
	7	1	3	1	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	43	22
	0-8								242	67	28
500 m	0	137	33	1	1	1	0	0	173	137	79
	1-3	94	22	0	1	0	0	0	117	22	19
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	22	19
	0-8								291	159	55
1000 m	0	243	22	5	4	0	0	0	261	230	88
	1-3	20	3	0	0	0	0	0	23	3	13
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	3	13
	0-8								284	233	82
Total	1-8								341	66	19
Total	0-8								817	470	58

Table A- 8 Total of measured and INPUFF2 predicted odour intensity data comparison using Equation 3.9

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	932	99	18	11	6	1		1067	932	87
	1-3	1474	458	86	43	12	0		2073	458	22
	4	473	164	27	14	3	0		681	27	4
	5	456	115	15	10	3	0		599	10	2
	6	289	95	23	13	0	0		420	0	0
	7	107	54	11	19	4	0		195	0	0
	8	29	4	2	0	1	0		36	0	0
	1-8								4004	495	12
	0-8								5071	1427	28
500 m	0	3714	499	5	2	0			4220	3714	88
	1-3	1737	321	3	0	0			2061	321	16
	4	83	21	0	0	0			104	0	0
	5	16	7	0	0	0			23	0	0
	6	5	3	0	0	0			8	0	0
	7	0	3	0	0	0			3	0	0
	8	0	0	0	0	0			0	0	0
	1-8								2199	321	15
	0-8								6419	4035	63
1000 m	0	5433	259	0	0	0			5692	5433	95
	1-3	437	16	0	0	0			453	16	4
	4	2	0	0	0	0			2	0	0
	5	2	0	0	0	0			2	0	0
	6	1	0	0	0	0			1	0	0
	7										
	8										
	1-8								458	16	3
	0-8								6150	5449	89
Total	1-8								6661	832	12
Total	0-8								17640	10911	62

Table A- 9 Total of measured and ISCST3 predicted odour intensity data comparison using Equation 5.3

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	30	12	0	0	0	0	0	42	30	71
	1-3	56	53	3	0	0	0	0	112	53	47
	4	18	23	0	0	0	0	0	41	0	0
	5	16	11	0	0	0	0	0	27	0	0
	6	8	6	0	0	0	0	0	14	0	0
	7	2	3	0	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	53	27
	0-8								242	83	34
500 m	0	143	30	0	0	0	0	0	173	143	83
	1-3	96	21	0	0	0	0	0	117	21	18
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	21	18
	0-8								291	164	56
1000 m	0	242	19	0	0	0	0	0	261	242	93
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	242	85
Total	1-8								341	74	22
Total	0-8								817	489	60

Table A- 10 Total of measured and AUSPLUME predicted odour intensity data comparison using Equation 5.3

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	26	16	0	0	0	0	0	42	26	62
	1-3	41	70	1	0	0	0	0	112	70	63
	4	15	26	0	0	0	0	0	41	0	0
	5	14	13	0	0	0	0	0	27	0	0
	6	5	9	0	0	0	0	0	14	0	0
	7	2	3	0	0	0	0	0	5	0	0
	8	1	0	0	0	0	0	0	1	0	0
	1-8								200	70	35
	0-8								242	96	40
500 m	0	130	41	2	0	0	0	0	173	130	75
	1-3	92	25	0	0	0	0	0	117	25	21
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	25	21
	0-8								291	155	53
1000 m	0	234	25	2	0	0	0	0	261	234	90
	1-3	20	3	0	0	0	0	0	23	3	13
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	3	13
	0-8								284	237	83
Total	1-8								341	98	29
Total	0-8								817	488	60

Table A- 11 Total of measured and CALPUFF predicted odour intensity data comparison using Equation 5.3

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	24	18	0	0	0	0	0	42	24	57
	1-3	53	58	1	0	0	0	0	112	58	52
	4	17	24	0	0	0	0	0	41	0	0
	5	14	13	0	0	0	0	0	27	0	0
	6	5	9	0	0	0	0	0	14	0	0
	7	2	3	0	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	58	29
	0-8								242	82	34
500 m	0	138	34	1	0	0	0	0	173	138	80
	1-3	90	27	0	0	0	0	0	117	27	23
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	27	23
	0-8								291	165	57
1000 m	0	240	21	0	0	0	0	0	261	240	92
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	240	85
Total	1-8								341	85	25
Total	0-8								817	487	60

Table A- 12 Total of measured and INPUFF2 predicted odour intensity data comparison using Equation 5.3.

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	930	128	6	3	0	0	0	1067	930	87
	1-3	1005	389	16	3	0	0	0	1413	389	28
	4	475	199	7	0	0	0	0	681	7	1
	5	908	341	9	1	0	0	0	1259	1	0
	6	282	137	1	0	0	0	0	420	0	0
	7	106	78	10	1	0	0	0	195	0	0
	8	26	9	1	0	0	0	0	36	0	0
	1-8								4004	397	10
	0-8								5071	1327	26
500 m	0	3686	533	1	0	0	0	0	4220	3686	87
	1-3	1516	278	0	0	0	0	0	1794	278	15
	4	80	24	0	0	0	0	0	104	0	0
	5	211	79	0	0	0	0	0	290	0	0
	6	4	4	0	0	0	0	0	8	0	0
	7	0	3	0	0	0	0	0	3	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								2199	278	13
	0-8								6419	3964	62
1000 m	0	5292	400	0	0	0	0	0	5692	5292	93
	1-3	407	23	0	0	0	0	0	430	23	5
	4	2	0	0	0	0	0	0	2	0	0
	5	23	2	0	0	0	0	0	25	0	0
	6	1	0	0	0	0	0	0	1	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								458	23	5
	0-8								6150	5315	86
Total	1-8								6661	698	10
Total	0-8								17640	10606	60

Table A- 13 Measured and ISCST3 predicted odour intensity data comparison using equation 3.9 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	29	3	2	8	0	0	0	42	29	69
	1-3	47	30	15	16	4	0	0	112	30	27
	4	16	7	13	3	2	0	0	41	13	32
	5	15	9	1	2	0	0	0	27	2	7
	6	6	5	2	1	0	0	0	14	0	0
	7	1	1	1	2	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	45	23
	0-8								242	74	31
500 m	0	141	30	2	0	0	0	0	173	141	82
	1-3	94	21	1	1	0	0	0	131	21	16
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								132	21	16
	0-8								305	162	53
1000 m	0	249	12	0	0	0	0	0	261	249	95
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	249	88
Total	1-8								341	66	19
Total	0-8								817	485	59

Table A- 14 Measured and AUSPLUME predicted odour intensity data comparison using Equation 3.9 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	24	5	6	6	1	0	0	42	24	57
	1-3	35	50	13	9	5	0	0	112	50	45
	4	11	19	9	1	1	0	0	41	9	22
	5	11	11	4	1	0	0	0	27	1	4
	6	3	6	4	1	0	0	0	14	0	0
	7	2	0	1	2	0	0	0	5	0	0
	8	1	0	0	0	0	0	0	1	0	0
	1-8								200	60	30
	0-8								242	84	35
500 m	0	117	46	5	3	2	0	0	173	117	68
	1-3	79	33	2	3	0	0	0	117	33	28
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	33	28
	0-8								291	150	52
1000 m	0	220	30	7	2	2	0	0	261	220	84
	1-3	20	2	1	0	0	0	0	23	2	9
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	2	9
	0-8								284	222	78
Total	1-8								341	95	28
Total	0-8								817	456	56

Table A- 15 Measured and CALPUFF predicted odour intensity data comparison using Equation 3.9 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	23	7	3	9	0	0	0	42	23	55
	1-3	41	35	18	15	3	0	0	112	35	31
	4	13	11	12	4	1	0	0	41	12	29
	5	11	13	1	2	0	0	0	27	2	7
	6	4	5	2	2	1	0	0	14	1	7
	7	1	1	2	1	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	50	25
	0-8								242	73	30
500 m	0	133	36	2	1	1	0	0	173	133	77
	1-3	88	27	1	1	0	0	0	117	27	23
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	27	23
	0-8								291	160	55
1000 m	0	239	20	1	1	0	0	0	261	239	92
	1-3	22	1	0	0	0	0	0	23	1	4
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	1	4
	0-8								284	240	85
Total	1-8								341	78	23
Total	0-8								817	473	58

Table A- 16 Measured and INPUFF2 predicted odour intensity data comparison using Equation 3.9 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	891	82	38	29	17	9	1	1067	891	84
	1-3	1253	433	179	132	55	19	2	2073	433	21
	4	414	132	59	49	23	4	0	681	59	9
	5	395	118	40	26	13	7	0	599	26	4
	6	230	98	36	26	20	10	0	420	20	5
	7	77	45	21	19	14	17	2	195	0	0
	8	27	4	1	3	0	1	0	36	0	0
	1-8								4004	538	13
	0-8								5071	1429	28
500 m	0	3436	632	120	21	10	1	0	4220	3436	81
	1-3	1581	372	57	35	16	0	0	2061	372	18
	4	67	34	3	0	0	0	0	104	3	3
	5	9	12	2	0	0	0	0	23	0	0
	6	2	6	0	0	0	0	0	8	0	0
	7	0	2	1	0	0	0	0	3	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								2199	375	17
	0-8								6419	3811	59
1000 m	0	5035	602	28	27	0	0	0	5692	5035	88
	1-3	407	44	2	0	0	0	0	453	44	10
	4	2	0	0	0	0	0	0	2	0	0
	5	2	0	0	0	0	0	0	2	0	0
	6	1	0	0	0	0	0	0	1	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								458	44	10
	0-8								6150	5079	83
Total	1-8								6661	974	15
Total	0-8								17640	10336	59

Table A- 17 Measured and ISCST3 predicted odour intensity data comparison using Equation 5.3 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	30	12	0	0	0	0	0	42	30	71
	1-3	51	58	3	0	0	0	0	112	58	52
	4	19	20	2	0	0	0	0	41	2	5
	5	17	10	0	0	0	0	0	27	0	0
	6	6	8	0	0	0	0	0	14	0	0
	7	1	4	0	0	0	0	0	5	0	0
	8	0	1	0	0	0	0	0	1	0	0
	1-8								200	60	30
	0-8								242	90	37
500 m	0	143	30	0	0	0	0	0	173	143	83
	1-3	94	23	0	0	0	0	0	117	23	20
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	23	19
	0-8								291	166	57
1000 m	0	238	23	0	0	0	0	0	261	238	91
	1-3	23	0	0	0	0	0	0	23	0	0
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	0	0
	0-8								284	238	84
Total	1-8								341	83	24
Total	0-8								817	494	60

Table A- 18 Measured and AUSPLUME predicted odour intensity data comparison using Equation 5.3 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	22	7	3	8	2	0	0	42	22	52
	1-3	29	52	13	9	8	1	0	112	52	46
	4	9	19	12	0	1	0	0	41	12	29
	5	6	16	4	1	0	0	0	27	1	4
	6	3	6	4	1	0	0	0	14	0	0
	7	2	1	0	2	0	0	0	5	0	0
	8	1	0	0	0	0	0	0	1	0	0
	1-8								200	65	33
	0-8								242	87	36
500 m	0	98	64	7	1	1	2	0	173	98	57
	1-3	64	46	3	2	2	0	0	117	46	39
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	46	39
	0-8								291	144	49
1000 m	0	169	74	9	5	2	2	0	261	169	65
	1-3	16	5	2	0	0	0	0	23	5	22
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	5	22
	0-8								284	174	61
Total	1-8								341	116	34
Total	0-8								817	405	50

Table A- 19 Measured and CALPUFF predicted odour intensity data comparison using Equation 5.3 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	22	8	2	5	5	0	0	42	22	52
	1-3	25	46	13	14	13	1	0	112	46	41
	4	6	16	12	3	4	0	0	41	12	29
	5	9	11	5	2	0	0	0	27	2	7
	6	4	4	3	1	2	0	0	14	2	14
	7	1	1	1	2	0	0	0	5	0	0
	8	0	0	1	0	0	0	0	1	0	0
	1-8								200	62	31
	0-8								242	84	35
500 m	0	118	50	2	1	1	1	0	173	118	68
	1-3	79	36	1	0	1	0	0	117	36	31
	4	0	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	1	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								118	36	31
	0-8								291	154	53
1000 m	0	208	51	1	0	1	0	0	261	208	80
	1-3	18	4	1	0	0	0	0	23	4	17
	4	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								23	4	17
	0-8								284	212	75
Total	1-8								341	102	30
Total	0-8								817	450	55

Table A- 20 Measured and INPUFF2 predicted odour intensity data comparison using Equation 5.3 and scaling factors.

Distance	Measured odour intensity	Model predicted odour intensity							Total	Total No. of agreed	Percentage of agreement (%)
		0	1-3	4	5	6	7	8			
100 m	0	930	128	6	3	0	0	0	1067	930	87
	1-3	1458	591	21	3	0	0	0	2073	591	29
	4	475	199	7	0	0	0	0	681	7	1
	5	455	139	4	1	0	0	0	599	1	0
	6	282	137	1	0	0	0	0	420	0	0
	7	106	78	10	1	0	0	0	195	0	0
	8	26	9	1	0	0	0	0	36	0	0
	1-8								4004	599	15
	0-8								5071	1529	30
500 m	0	3686	533	1	0	0	0	0	4220	3686	87
	1-3	1715	346	0	0	0	0	0	2061	346	17
	4	80	24	0	0	0	0	0	104	0	0
	5	12	11	0	0	0	0	0	23	0	0
	6	4	4	0	0	0	0	0	8	0	0
	7	0	3	0	0	0	0	0	3	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								2199	346	0
	0-8								6419	4032	0
1000 m	0	5292	400	0	0	0	0	0	5692	5292	0
	1-3	428	25	0	0	0	0	0	453	25	0
	4	2	0	0	0	0	0	0	2	0	0
	5	2	0	0	0	0	0	0	2	0	0
	6	1	0	0	0	0	0	0	1	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0
	1-8								458	25	5
	0-8								6150	5317	86
Total	1-8								6661	970	15
Total	0-8								17640	10878	62

12. Appendix B: Detailed Agreement Analysis Results Of The Modeled And Measured Odour Intensities Using University of Minnesota's Plume Measurement Data

Table B- 1 Total measured and CALPUFF predicted odour intensity data comparison using Equation 3.6.

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
100 m	0	0	4	4	0	0	0	8	0	0
	1	1	2	16	3	1	0	23	2	9
	2	0	1	11	6	2	0	20	11	55
	3	0	0	2	2	1	0	5	2	40
	4	0	0	1	0	1	0	2	1	0
	5	0	0	0	0	0	0	0	0	0
	1-5							50	16	32
	0-5							58	16	28
200 m	0	2	2	5	0	0	0	9	2	22
	1	0	1	0	0	0	0	1	1	0
	2	0	0	0	2	0	0	2	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							3	1	33
	0-5							12	3	25
300 m	0	0	0	1	0	0	0	1	0	0
	1	0	0	0	1	0	0	1	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							1	0	0
	0-5							2	0	0
Total	1-5							54	17	31
Total	0-5							72	19	26

Table B- 2 Total measured and INPUFF2 predicted odour intensity data comparison using Equation 3.6

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
100 m	0	2	5	1	0	0	0	8	2	25
	1	4	12	6	0	1	0	23	12	52
	2	1	7	9	3	0	0	20	9	45
	3	0	1	2	2	0	0	5	2	40
	4	0	0	2	0	0	0	2	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							50	23	46
	0-5							58	25	43
200 m	0	4	5	0	0	0	0	9	4	44
	1	1	0	0	0	0	0	1	0	0
	2	0	0	1	1	0	0	2	1	50
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							3	1	33
	0-5							12	5	42
300 m	0	0	1	0	0	0	0	1	0	0
	1	0	0	1	0	0	0	1	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							1	0	0
	0-5							2	0	0
Total	1-5							54	24	44
Total	0-5							72	30	42

13. APPENDIX C: DETAILED AGREEMENT ANALYSIS RESULTS OF THE MODELED AND MEASURED ODOUR INTENSITIES USING UNIVERSITY OF SASKATCHEWAN'S PLUME MEASUREMENT DATA

Table C- 1 Measured and CALPUFF predicted odour intensity data comparison using Equation 3.6

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
500 m	0	8	5	0	0	0	0	13	8	62
	1	4	3	0	0	0	0	7	3	43
	2	3	4	1	0	0	0	8	1	13
	3	0	1	0	0	0	0	1	0	0
	4	1	3	0	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							21	4	19
	0-5							34	12	35
1000 m	0	14	6	0	0	0	0	20	14	70
	1	8	2	0	0	0	0	10	2	20
	2	5	1	0	0	0	0	6	0	0
	3	3	2	0	0	0	0	5	0	0
	4	0	1	0	0	0	0	1	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							22	2	9
	0-5							42	16	38
1km~3km	0	196	77	0	0	0	0	273	196	72
	1	53	20	0	0	0	0	73	20	27
	2	21	9	0	0	0	0	30	0	0
	3	14	9	0	0	0	0	23	0	0
	4	8	2	0	0	0	0	10	0	0
	5	4	4	0	0	0	0	8	0	0
	1-5							144	20	14
	0-5							417	216	52
3000 m	0	244	33	0	0	0	0	277	244	88
	1	33	4	0	0	0	0	37	4	11
	2	17	1	0	0	0	0	18	0	0
	3	6	1	0	0	0	0	7	0	0
	4	3	1	0	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							67	4	6
	0-5							344	248	72
Total	1-5							254	30	12
Total	0-5							837	492	59

Table C- 2 Measured and INPUFF2 predicted odour intensity data comparison using Equation 3.6

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
500 m	0	13	0	0	0	0	0	13	13	100
	1	5	2	0	0	0	0	7	2	29
	2	5	3	0	0	0	0	8	0	0
	3	1	0	0	0	0	0	1	0	0
	4	2	2	0	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							21	2	10
	0-5							34	15	44
1000 m	0	19	1	0	0	0	0	20	19	95
	1	10	0	0	0	0	0	10	0	0
	2	5	1	0	0	0	0	6	0	0
	3	5	0	0	0	0	0	5	0	0
	4	1	0	0	0	0	0	1	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							22	0	0
	0-5							42	19	45
1km~3km	0	260	13	0	0	0	0	273	260	95
	1	69	4	0	0	0	0	73	4	6
	2	28	2	0	0	0	0	30	0	0
	3	19	4	0	0	0	0	23	0	0
	4	10	0	0	0	0	0	10	0	0
	5	7	1	0	0	0	0	8	0	0
	1-5							144	4	3
	0-5							417	264	63
3000 m	0	277	0	0	0	0	0	277	277	100
	1	37	0	0	0	0	0	37	0	0
	2	18	0	0	0	0	0	18	0	0
	3	7	0	0	0	0	0	7	0	0
	4	4	0	0	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							67	0	0
	0-5							344	277	81
Total	1-5							254	6	2
Total	0-5							837	575	69

Table C- 3 Measured and CALPUFF predicted odour intensity data comparison using Equation 3.6 and scaling factors

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
500 m	0	2	8	3	0	0	0	13	2	15
	1	2	5	0	0	0	0	7	5	71
	2	3	0	3	1	1	0	8	3	38
	3	0	1	0	0	0	0	1	0	0
	4	2	0	0	2	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							21	8	38
	0-5							34	10	29
1000 m	0	17	1	2	0	0	0	20	17	85
	1	6	4	0	0	0	0	10	4	40
	2	3	3	0	0	0	0	6	0	0
	3	3	2	0	0	0	0	5	0	0
	4	0	0	1	0	0	0	1	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							22	4	18
	0-5							42	21	50
1km~3km	0	187	75	8	3	0	0	273	187	68
	1	32	38	2	1	0	0	73	38	52
	2	14	14	2	0	0	0	30	2	7
	3	11	11	1	0	0	0	23	0	0
	4	5	5	0	0	0	0	10	0	0
	5	5	2	1	0	0	0	8	0	0
	1-5							144	40	28
	0-5							417	227	54
3000 m	0	188	88	0	1	0	0	277	188	68
	1	16	20	0	1	0	0	37	20	54
	2	9	9	0	0	0	0	18	0	0
	3	4	3	0	0	0	0	7	0	0
	4	3	1	0	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							67	20	30
	0-5							344	208	61
Total	1-5							254	72	28
Total	0-5							837	466	56

Table C- 4 Measured and INPUFF2 predicted odour intensity data comparison using Equation 3.6 and Scaling Factors

Distance	Measured odour intensity	Model predicted odour intensity						Total	Total No. of agreed	Percentage of agreement (%)
		0	1	2	3	4	5			
500 m	0	8	5	0	0	0	0	13	8	62
	1	3	2	2	0	0	0	7	2	29
	2	3	2	1	2	0	0	8	1	13
	3	1	0	0	0	0	0	1	0	0
	4	2	0	2	0	0	0	4	0	0
	5	1	0	0	0	0	0	1	0	0
	1-5							21	3	14
	0-5							34	11	32
1000 m	0	16	3	1	0	0	0	20	16	80
	1	8	2	0	0	0	0	10	2	20
	2	5	0	1	0	0	0	6	1	17
	3	3	2	0	0	0	0	5	0	0
	4	1	0	0	0	0	0	1	0	0
	5	0	0	0	0	0	0	0	0	0
	1-5							22	3	14
	0-5							42	19	45
1km~3km	0	194	70	7	2	0	0	273	194	71
	1	44	25	2	2	0	0	73	25	34
	2	17	12	1	0	0	0	30	1	3
	3	10	11	2	0	0	0	23	0	0
	4	6	4	0	0	0	0	10	0	0
	5	4	4	0	0	0	0	8	0	0
	1-5							144	26	18
	0-5							417	220	53
3000 m	0	216	61	0	0	0	0	277	216	78
	1	27	10	0	0	0	0	37	10	27
	2	10	8	0	0	0	0	18	0	0
	3	5	2	0	0	0	0	7	0	0
	4	3	1	0	0	0	0	4	0	0
	5	0	1	0	0	0	0	1	0	0
	1-5							67	10	15
	0-5							344	226	66
Total	1-5							254	42	17
Total	0-5							837	476	57