EVALUATION OF AERMOD AND CALPUFF 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

By

Yuguo Li

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Agricultural and Bioresource Engineering

University of Saskatchewan

Saskatoon, Saskatchewan S7N 5A9

ABSTRACT

Impact of odour emissions from livestock operation sites on the air quality of neighboring areas has raised public concerns. A practical means to solve this problem is to set adequate setback distance. Air dispersion modeling was proved to be a promising method in predicting proper odour setback distance. Although a lot of air dispersion models have been used to predict odour concentrations downwind agricultural odour sources, not so much information regarding the capability of these models in odour dispersion modeling simulation could be found because very limited field odour data are available to be applied to evaluate the modeling result. A main purpose of this project was evaluating AERMOD and CALPUFF air dispersion models for odour dispersion simulation using field odour data.

Before evaluating and calibrating AERMOD and CALPUFF, sensitivity analysis of these two models to five major climatic parameters, i.e., mixing height, ambient temperature, stability class, wind speed, and wind direction, was conducted under both steady-state and variable meteorological conditions. It was found under steady-state weather condition, stability class and wind speed had great impact on the odour dispersion; while, ambient temperature and wind direction had limited impact on it; and mixing height had no impact on the odour dispersion at all. Under variable weather condition, maximum odour travel distance with odour concentrations of 1, 2, 5 and 10 OU/m^3 were examined using annual hourly meteorological data of year 2003 of the simulated area and the simulation result showed odour traveled longer distance under the prevailing wind direction.

Evaluation outcomes of these two models using field odour data from University of Minnesota and University of Alberta showed capability of these two models in odour dispersion simulation was close in terms of agreement of modeled and field measured odour occurrences. Using Minnesota odour plume data, the difference of overall agreement of all field odour measurements and model predictions was 3.6% applying conversion equation from University of Minnesota

and 3.1% applying conversion equation from University of Alberta between two models. However, if field odour intensity 0 was not considered in Minnesota measured odour data, the difference of overall agreement of all field odour measurements and model predictions was 3.1% applying conversion equation from University of Minnesota and 1.6% applying conversion equation from University of Alberta between two models. Using Alberta odour plume data, the difference of overall agreement of all field odour measurements and model predictions was 0.7% applying conversion equation from University of Alberta and 1.2% applying conversion equation from University of Minnesota between two models. However, if field odour intensity 0 was not considered in Alberta measured odour data, the difference of overall agreement of all field odour measurements and model predictions was 0.4% applying conversion equation from University of Alberta and 0.7% applying conversion equation from University of Minnesota between two models. Application of scaling factors can improve agreement of modeled and measured odour intensities (including all field odour measurements and field odour measurements without intensity 0) when conversion equation from University of Minnesota was used.

Both models were used in determining odour setback distance based on their close performance in odour dispersion simulation. Application of two models in predicting odour setback distance using warm season (from May to October) historical annul hourly meteorological data (from 1999 to 2002) for a swine farm in Saskatchewan showed some differences existed between models predicted and Prairie Provinces odour control guidelines recommended setbacks. Accurately measured field odour data and development of an air dispersion model for agricultural odour dispersion simulation purpose as well as acceptable odour criteria could be considered in the future studies.

ACKNOWLEDGEMENTS

I would like to thank my research supervisor, Dr. Huiqing Guo, for her professional guidance, support, and trust in my abilities during my graduate study. I would also like to thank my Graduate Advisory Committee members, Drs. Bernardo Z. Predicala and Scott D. Noble, for their valuable comments and constructive advices for this thesis and help through my master studies. Thanks also extend to Dr. Li Chen for serving as external examiner of this thesis.

Thanks also go to Zimu Yu, Yuanyuan Wang, Yanan Xing; faculty and staff in the Department of Agricultural and Bioresource Engineering for your support to finish my master program here.

I thank the financial assistance from the NSERC and provision of field odour plume data by University of Minnesota and University of Alberta.

Finally, I thank my family and friends for their support during the process of my studying. Without their encouragement, I cannot finish this studying.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAFRD	Alberta Agriculture Food and Rural Development
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
ASTM	American Society of Testing and Materials
AUs	Animal Units
AUSPLUME	Australian Plume Model
CAFOs	Concentrated Animal Feeding Operations
CDD	Critical Odour Detection Distance
C5	Atmospheric stability C with wind speed 5 m/s
D1	Atmospheric stability C with wind speed 1 m/s
D2	Atmospheric stability D with wind speed 2 m/s
D3	Atmospheric stability D with wind speed 3 m/s
D4	Atmospheric stability D with wind speed 4 m/s
D5	Atmospheric stability D with wind speed 5 m/s
D6	Atmospheric stability D with wind speed 6 m/s
D8	Atmospheric stability D with wind speed 8 m/s

D15	Atmospheric stability D with wind speed 15 m/s
EMS	Earth Manure Storage
E2	Atmospheric stability E with wind speed 2 m/s
E3	Atmospheric stability E with wind speed 3 m/s
E4	Atmospheric stability E with wind speed 4 m/s
E5	Atmospheric stability E with wind speed 5 m/s
FB	Fractional Bias
F2	Atmospheric stability F with wind speed 2 m/s
F3	Atmospheric stability F with wind speed 3 m/s
GPS	Global Positioning System
GUI	Graphical User Interface
ILOs	Intensive Livestock Operations
INPUFF-2	Integrated PUFF version 2
ISC	Industrial Source Complex
ISCST3	Industrial Source Complex Short Term version 3
MDS-Π	Ontario’s Minimum Distance Separation guidelines
MSL	Mean Sea Level

NCDC	National Climatic Data Center
NNW	North-northwest
NSERC	Natural Sciences and Engineering Research Council
NWS	National Weather Service
OB	Observed
ODT	Odour Detection Threshold
OFFSET	Odour for Feedlots Setback Estimation Tool
OU	Odour Unit
OU/m^3	Odour Units per cubic meter
PR	Predicted
S	South
SF	Scaling Factor
SW	Southwest
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
W	West

1. INTRODUCTION

Construction of new livestock facilities or expansion of existing ones has become increasingly difficult due to the concerns of residents surrounding Intensive Livestock Operations (ILOs). Such concerns often include the impact of nuisance odour on peoples' lives and on the environment (Jacobson et al., 2002). Among all the currently used odour control technologies, e.g., diet modification, manure treatment, capture and treatment of emitted gases, etc., keeping adequate buffer distance (setback distance) between odour sources and neighboring residential areas seems to be an effective and economical approach (Sweeten et al., 2001). Generally, determination of setback distance can be accomplished by two methods: use of established agricultural odour control guidelines or air dispersion models. The guideline approach primarily utilizes empirical personal judgment and/or simple distance calculating equations, while air dispersion models approach considers every factor that may affect odour dispersion in the vicinity of odour source, making it more scientific and promising (Jacobson et al., 2002).

A lot of researchers have employed air dispersion models in agricultural odour dispersion simulation to predict concentrations of odour and other air contaminants downwind animal production sites since the early 1980s (Janni, 1982; Mejer and Krause, 1985; Carnry and Dodd, 1989; Ormerod, 1991; Chen et al., 1998; Diosey et al., 2000; Zhu et al., 2000; Koppolu et al., 2002; Guo et al., 2004a; Jacobson et al., 2005; Zhou et al., 2005). These models varied from pretty simple to quite complicated, including the theories used to explain the process of odour dispersion, input parameters of the models and equations involved in calculation. With accessibility to original field odour data obtained by odour observers during the last few years, evaluation of these models became possible through comparing models predicted odours with corresponding field measured ones, making the simulation results of these models more convictive.

An advanced United States Environmental Protection Agency (USEPA) guideline model, CALPUFF, has drawn attention because of its good performance in agricultural odour dispersion simulation compared with other models (USEPA, 1998; Allwine et al., 1998; Walker et al., 2002; Wang et al., 2005; Xing, 2006; Curran et al., 2007; Henry et al., 2007; Thomas et al., 2007). Application of AERMOD, a newly introduced regulatory model of EPA, to simulate odour dispersion may be found in literatures; however, justification of some algorithms in AERMOD is still necessary. Accuracy of this model in predicting odour concentration is still needed to be clarified and validated (USEPA, 2002). By comparing this model with CALPUFF, we may find its capability in simulating odour dispersion. This project is intended to evaluate AERMOD and CALPUFF air dispersion models by comparing model predictions with field measurements and to use the better one in these two models to predict odour setback distances for a typical sized swim farm.

2. LITERATURE REVIEW

Concentrated Animal Feeding Operations (CAFOs), including swine and poultry operations, dairies and cattle feedlots, and the associated animal waste storages may produce emissions of odour, particulate matter, and greenhouse gases (Sweeten et al., 2001). This project only focuses on odour. After being released, odour will transport and disperse in atmosphere. It may reach residential area located in the vicinity of the CAFOs thus incurring complaints from residents living there.

2.1 Measurement of Odour

Odour is humans' olfactory response to the odourous gases, indicating it is a subjective sensation and may vary for different people. The main characteristics of odour-caused nuisance conditions are concentration, intensity, persistence, frequency, and hedonic tone (Jones, 1992). The concentration and intensity are two most important characteristics among them because they are frequently used by researchers to deal with odour related issues and besides they are the only two parameters involved in the work of model evaluation.

2.1.1 Measurement of Odour Concentration

Odour concentration is widely measured through the method of olfactometry. In this technique, the odour sample is diluted using odour-free air until the odour sample has a 50 percent probability of being detected by a group of human panelists for sniffing odour, i.e., 50 percent of the odour sniffers can discriminate the odour sample from the odour-free sample. Odour concentration is the dilution ratio corresponding to 50% of the correct responses (CEN, 1999).

Odour concentration measured by olfactometry is expressed as "odour units" (OU) or "odour units per cubic meter" (OU/m^3). OU is defined as the volume of diluents required to dilute a unit volume of odour until the odour detection threshold (ODT) of the odour is obtained (Sweeten, et al., 2001) while OU/m^3 is the concentration of odour in one cubic meter of air at the ODT of the odour (NCMAWM, 2001). Most of the models including AERMOD and CALPUFF require input of odour emission rate(s) from odour source(s) in the dimension of mass/time (e.g., g/s, kg/hr, etc.) and output of odour concentration of mass/m^3 (e.g., g/m^3, mg/m^3, etc.), however, odour emission rate(s) measured at odour source(s) takes unit of OU/s. Researchers employed OU/s instead of g/s as the input emission rate dimension and OU/m^3 instead of g/m^3 as the output dimension of models (Williams, 1986; Caeney and Dodd, 1989; Ormerod, 1991; Smith, 1993; Zhu et al., 1998; Guo et al., 2001a). Zhu et al. (2000) proposed that use of OU/s not mass/time may be one of reasons for the low concentrations predicted by the model INFUFF-2 and scaling factor(s) could be employed to reduce the errors caused by it. In this project, OU/s will be used as the dimension of model input, which corresponds to the mass concentration unit of g/s. Odour concentration at the receptor's location, i.e., the output of the model, has the unit of OU/m^3.

2.1.2 Measurement of Odour Intensity

Odour intensity is defined as the relative perceived psychological strength of an odour that is above the ODT (Sweeten et al., 2001). Intensity can be assessed via either category or referencing scales. Commonly, the latter one is preferred by researchers because it allows direct comparisons between research studies thus improving reproducibility and work efficiency. However, barriers will be encountered due to different odourant concentrations and category scales are used by different researchers if category scales approach is applied (Harssema, 1991).

Intensity assessed through referencing scales is evaluated by either dynamic or static scale method (ASTM, 1988). The dynamic odour intensity referencing scales are based on the ppm (part per million) of n-butanol in air while the static odour intensity referencing scales are based on the ppm of n-butanol in water. Commonly, odour inspecting activities, including laboratory odour testing, field odour monitoring, etc., utilize the static odour intensity referencing scales (Sweeten et al., 2001). Field odour intensities are observed by a group of panelist sniffers standing in the field downwind odour sources. Training of odour sniffers in laboratory to sniff odour intensities is called nasal ranger training, which is a fundamental activity before field odour monitoring (McGinley et al., 2002).

Two kinds of widely used referencing scales by odour study researchers are 5-point (0 - 5) and 8-point (0 - 8) scales. Use of 5-point scales could be found in Jacobson et al. (1999); Zhu et al. (2000); Guo et al. (2001a), and 8-point scales in Zhang et al. (2002, 2005) and Feddes and Segura, (2005), etc. Comparison of the two kinds of scales showed the 5-point scales will achieve higher odour concentration than 8-point scales for the same n-butanol concentration in water. For example, for the n-butanol concentration of around 240 ppm, the odour concentration is 25 OU/m^3 in 5-point scales and 5 OU/m^3 in 8-point scales. This will result in the different relationship between odour concentration and intensity (Guo et al., 2006).

2.1.3 Relationship between Odour Concentration and Intensity

The relationship between odour concentration and intensity is the bridge linking odour intensity data measured in the field with odour concentration predicted by air dispersion models. Two options can be used to compare field measured and model predicted odour. One is to convert field measured odour intensities to concentrations and the alternative is to convert model predicted concentrations to intensities. Both of these two options involve the concentration-intensity conversion equation. The relationship between these two variables is not linear, and varies for different odour and odourants. Steven's Law, a power function equation, is usually used to express relationship between them (US National Research Council, 1979).

Although odour study researchers have created different equations to describe the relationship between these two variables, they all followed this format.

In Guo et al. (2001a), a total of 179 odour samples were collected from buildings and earthen manure storages (EMS) from swine and dairy farms and measured for both intensity and concentration by trained panelists in the olfactometry laboratory in University of Minnesota during 1998 and 1999. 5-point intensity scales were used by them. The relationships between odour intensity and concentration created by the researcher using datasheet developed by the panelists were:

Swine odour: $I = 0.93\ln(C) - 1.986$ ($R^2 = 0.69$) (2.1)

Dairy odour: $I = 0.92\ln(C) - 2.075$ ($R^2 = 0.89$) (2.2)

Where I is the odour intensity on 0 - 5 scales, C is the odour concentration (OU/m^3), R is the sample coefficient of determination

In Feddes and Segura, (2005), the relationship between the perceived odour intensity and concentration was developed using standard 60-mL training jars containing different n-butanol concentrations. The 8-point odour intensity referencing scales measured by odour sniffers and the corresponding n-butanol concentration (OU/m^3) determined by an olfactometer in that laboratory was:

$I = 1.245\ln(C) - 0.046$ ($R^2 = 0.79$) (2.3)

Where I is the odour intensity on 0 - 8 scales, C is the odour concentration (OU/m^3), R is the sample coefficient of determination.

According to Zhang et al. (2002), the relationship between odour intensity of bagged samples assessed by nasal rangers in the laboratory in the University of Manitoba and the corresponding odour concentration measured with an olfactometer for short distances can be expressed as:

$$I = \ln(C) + 0.36 \ (R^2 = 0.61) \qquad (2.4)$$

Where I is the odour intensity on 0 - 8 scales, C is the odour concentration (OU/m^3), R is the sample coefficient of determination.

The details of relationship between odour intensity and concentration used in these two referencing scales are shown in Tables 2.1 and 2.2.

Table 2.1 Odour intensity referencing scale of 0 - 5 scale (Guo et al., 2001a)

Odour referencing scale	Odour intensity	Odour strength	n–Butanol in Water (ppm)	Odour concentration (OU/m^3)	Odour concentration range (OU/m^3)
0 to 5	0	No odour	0	0	< 14
	1	Very faint	250	25	14 - 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

Table 2.2 Odour intensity referencing scale of 0 - 8 scale (Xing, 2006)

Odour referencing scale	Odour intensity	Odour strength	n–Butanol in Water (ppm)	Odour concentration (OU/m^3) by Feddes and Segura, (2005)	Odour concentration range (OU/m^3)
0 to 8	0	No odour	0	1	< 2
	1	Not annoying	120	2	2 - 3
	2	A little annoying	240	5	3 - 8
	3	A little annoying	480	12	8 - 17
	4	Annoying	960	26	17 - 39
	5	Annoying	1940	58	39 - 86
	6	Very annoying	3880	128	86 - 192
	7	Very annoying	7750	287	192 - 429
	8	Extremely Annoying	15500	640	> 429

2.2 Odour Dispersion Modeling

Before using of air dispersion models to simulate odour dispersion, we should consider issues related to odour dispersion modeling, such as the characteristics of the odour, what factors may influence the dispersion of the odour in atmosphere, and detailed information of the models that used to conduct odour dispersion simulation. Knowing these gives us the sense how the models work and whether what we have done are correct.

2.2.1 Factors Affecting Odour Dispersion

Dispersion of odours is mainly impacted by topography around the odour source and atmospheric condition (Jacobson et al., 2005). When Jacques Whitford Environment Ltd. (2003) employed CALPUFF to predict Minimum Separation Distance (MSD) from agricultural odour sources in Alberta, it was found topography and screening (windbreak or shelterbelt) had great influence on MSD. The effect of vegetation screening on dispersion was very dependent on the dimensions of the screen and its location relative to the odour emission sources. Kelly, (1995) proposed that a sound selection of CAFOs for good odour dispersion should be gently sloped topography without confining valley walls. Because atmospheric condition is changeable and an important input of air dispersion models, it always attracted researchers' attention when carrying out researches related to odour issues (Zhu, 1999; Jacobson et al., 2000; Guo et al., 2001b; etc.). Ouellette et al. (2006) concluded that atmospheric condition was a very important factor involved when using a window-based air dispersion model to carry out odour dispersion simulation. The major parameters used to describe atmospheric condition are ambient temperature, mixing height, atmospheric stability class, wind speed, wind direction, relative humidity, and solar radiation (Guo et al., 2001b).

According to Jacobson et al. (2000), atmospheric stability class has substantial impact on odour dispersion. Atmospheric stability is generally described using Pasquill atmospheric stability class categories A - G (A: strongly unstable, B: moderately unstable, C: slightly unstable, D: neutral, E: slightly stable, F: moderately stable, and G: strongly stable), which are widely used in most dispersion models (USEPA, 1999). According to Guo et al. (2001b), the most unstable weather occurs under strongly unstable stability class A with high wind speed, while the most stable weather occurs when stability class is G and the wind speed is relatively low. Stable atmospheric conditions that usually occur at night favor odour transport thus producing a lot of complaints from residents; however, unstable atmosphere happens at most of the time during daytime disfavor odour transport thus relieving people from odour nuisance. Xing, (2007) conducted the sensitivity analysis of four models, i.e., ISCST3, AUSPLUME, CALPUFF, and INPUFF-2 to find the wind speed had potential impact on odour dispersion followed by atmospheric stability class. It was also found that ambient temperature had very limited impact on odour dispersion, while mixing height had no influence at odour dispersion at all.

2.2.2 Models Used in Odour Dispersion Modeling

Air dispersion models were broadly divided into Gaussian plume models (steady-state models) and advanced models (unsteady-state models) (New Zealand National Institute of Water and Atmospheric Research, 2004). Gaussian plume models, which have been applied in practical use for a long time, are well understood and have received wide approval. Although been created some years later than Gaussian-plume models, advanced models have been in use for scientific research for decades, and now are getting more and more good appraisement based on their performances in odour dispersion simulation (New Zealand National Institute of Water and Atmospheric Research, 2004).

2.2.2.1 Gaussian Plume Models

The Gaussian plume model (e.g., AUSPLUME, ISCST3) is the most commonly developed air dispersion model. It is the base of developing most dispersion calculations for the continuous pollution source in the uniform dispersion field (Arya, 1999). Figure 2.1 shows the approach of a typical point source pollution dispersion in the Gaussian plume modeling. It can be observed from the figure the bell-shaped distribution of the pollution plume is the same in every direction in the three dimensional space.

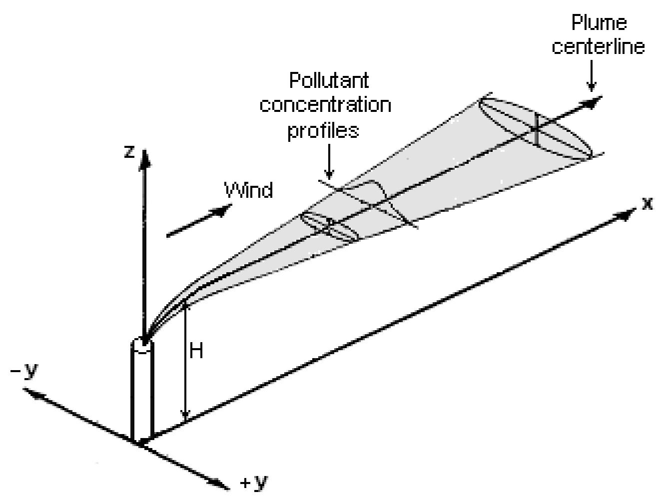


Figure 2.1 A typical plume from an elevated point source in the Gaussian plume modeling (adapted from New Zealand National Institute of Water and Atmospheric Research, 2004)

The Gaussian plume formula can be expressed as (Arya, 1999):

$$C(x, y, z) = \frac{Q}{2\pi\delta_y\delta_z U} \exp\left[-0.5\left(\frac{y}{\delta_y}\right)^2\right] \left\{\exp\left[-0.5\left(\frac{z-H}{\delta_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z+H}{\delta_z}\right)^2\right]\right\} \quad (2.5)$$

Where: C is steady-state concentration at a specific point (g/m^3); Q is emission rate of pollutant (g/s); δ_y and δ_z are horizontal and vertical standard deviations of plume concentration, which is the function of x; 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 the centerline concentration of ground-level odour source (e.g., agricultural odour source), the value of $z = H = y = 0$, so we get:

$$C(x) = \frac{Q}{2\pi\delta_y\delta_z U} \tag{2.6}$$

Formula used in Gaussian plume models was derived from the assumption that the whole field where the pollutant disperses is in 'steady-state' condition. Some limitations originally existed because of this assumption (New Zealand National Institute of Water and Atmospheric Research, 2004). For example, when calculating each hour's concentration (most of the Gaussian models calculate concentration for each single hour), it excludes the effect of contaminants of previous hours. Due to limitations, this kind of model can be used under situations where the topography is relatively flat without complicated terrain as hills, rivers, or bumps; the meteorology is "simple", i.e., pretty uniform in spatiality, and without many calm conditions (New Zealand National Institute of Water and Atmospheric Research, 2004).

2.2.2.2 Lagrangian Puff Models

Advanced models were grouped into three categories: Particles, Puff, and Grid points depending on the way the air pollutants are represented. Puff model (e.g., INPUFF-2, RIMPUFF) is the most widely used advanced model because it can under most circumstances effectively consider the real meteorological condition to be simulated (New Zealand National Institute of Water and Atmospheric Research, 2004). Although puff model requires three-dimensional meteorological data, it can also use the measurements from a weather observation tower as used in other models as ISCST3. Figure 2.2 illustrates the approach puffs travel in atmosphere from a point source adopted by puff models.

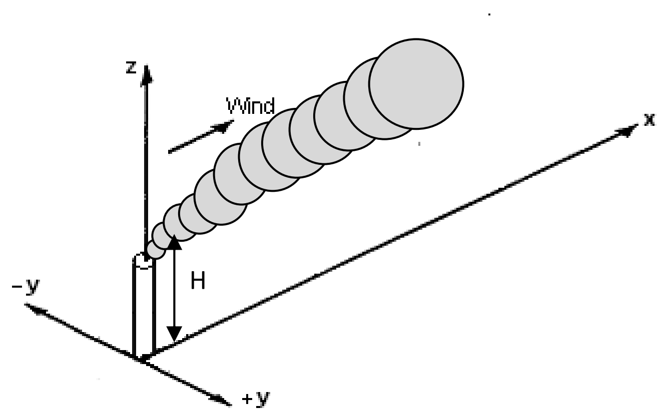


Figure 2.2 A typical plume from an elevated point source in the Lagrangian puff modeling (adapted from New Zealand National Institute of Water and Atmospheric Research, 2004)

The Lagrangian puff formula can be expressed as (Arya, 1999):

$$C(x, y, z) = \frac{Q_{ip}}{(2\pi)^{1.5}\delta_x\delta_y\delta_z U} \exp\left[-0.5\left(\frac{x}{\delta_x}\right)^2 - 0.5\left(\frac{y}{\delta_y}\right)^2\right] \left\{\exp\left[-0.5\left(\frac{z-H}{\delta_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z+H}{\delta_z}\right)^2\right]\right. \quad (2.7)$$

Where: Q_{ip} is the instantaneous point source emission rate; the other variables have the same meaning as in equation 2.5.

For centerline concentration of ground-level odour source (e.g., agricultural odour source), the value of $y = z = H = 0$, so we get:

$$C(x, y) = \frac{2Q_{ip}}{(2\pi)^{1.5}\delta_x\delta_y\delta_z U} \exp\left[-0.5\left(\frac{x}{\delta_x}\right)^2\right] \quad (2.8)$$

From equations 2.5 and 2.8 we can see the theoretical basis of two models for ground-level pollution sources is the same; however, puff models consider time-dependent and longitudinal dispersion.

Although puff dispersion model is more sophisticated and can better represent actual weather condition, it still has some demerits compared with plume models. For example, it is more difficult to handle the weather data in Puff models. Puff model is suggested to be used in some circumstances as when the meteorological condition or terrain is very complicated or the period of low wind speed happens frequently (New Zealand National Institute of Water and Atmospheric Research, 2004).

2.2.3 Review of Models Involved in This Project

AERMOD and CALPUFF will be used in this project. This part will provide some descriptions of these two models found in the literature.

2.2.3.1 AERMOD

AERMOD was adopted by U.S. EPA as its regulatory model from December 9th of 2005 (USEPA, 2005). There are three regulatory modules of the AERMOD modeling system: AERMET, AERMAP, and AERMOD*. AERMET is a meteorological data preprocessor that prepares meteorological data to be used in AERMOD; AERMAP is a terrain data preprocessor that prepares topographical data to be used in AERMOD; and AERMOD* is a postprocessor that combines meteorological and topographical data and information of odour receptors and odour emissions to yield the odour concentrations downwind odour source (USEPA, 2004b).

AERMOD is a Gaussian plume model that updated from the Industrial Source Complex Short Term version 3 (ISCST3) model. It incorporates air dispersion that based on planetary boundary layer (PBL) turbulence structure and scaling concepts, including treatment of both surface and elevated sources for both simple and complex terrain (USEPA, 2003). Compared with ISCST3, some new or improved algorithms were applied in AERMOD. For example, it can handle elevated, near-surface, and surface level sources; it can treat receptors on complex terrain, etc. It showed good performance in dealing with point, volume, area, and area-polygon and area-circle source types for short distance odour dispersion simulation by Iowa Department of Natural Resources Animal Feeding Operations Technical Workgroup (2004).

Meteorological data used in AERMOD* are the final output of AERMET, which is a kind of software prepared to yield Surface File and Profile File to be accepted by AERMOD*. So, AERMET and AERMOD* must be run in sequence in order to get the final desired odour concentration. A whole run of AERMET contains three stages (Figure 2.3) and it needs three types of data, i.e., National Weather Service (NWS) hourly surface observations, NWS twice-daily upper air soundings, and data collected from an on-site weather data measurement tower (USEPA, 2004a). The first stage in AERMET is to extract data from the stored compact format by NWS; the second stage is to combine data extracted from stage one for 24-hour period of time; and the final stage merges the data from stage two to develop surface and profile file to be used in AERMOD* (USEPA, 2004a). Normally, if raw surface data contains enough information needed to run AERMET then it together with upper air data will be enough to get final desired output if on-site data are not available. The upper air and surface data are available from the U.S. National Climatic Data Center (NCDC). The data prepared by NCDC are stored in some specific formats, including the upper air sounding data in TD-6201 format, hourly surface weather observations in CD-144 format (time-based format) or TD-3280 format (element-based format) (USEPA, 2004a).

A notable difference between AERMOD and other used models is it adopted three parameters, i.e., albedo, Bowen ratio, and surface roughness length, to characterize the weather condition instead of commonly used variable, Pasquill stability class, in other models. The albedo is the fraction of total solar radiation reflected by the earth surface back to atmosphere. The Bowen ratio is the ratio of the sensible heat flux to the latent heat flux. And the roughness length is the height at which the mean horizontal wind speed is zero (USEPA, 2004a).

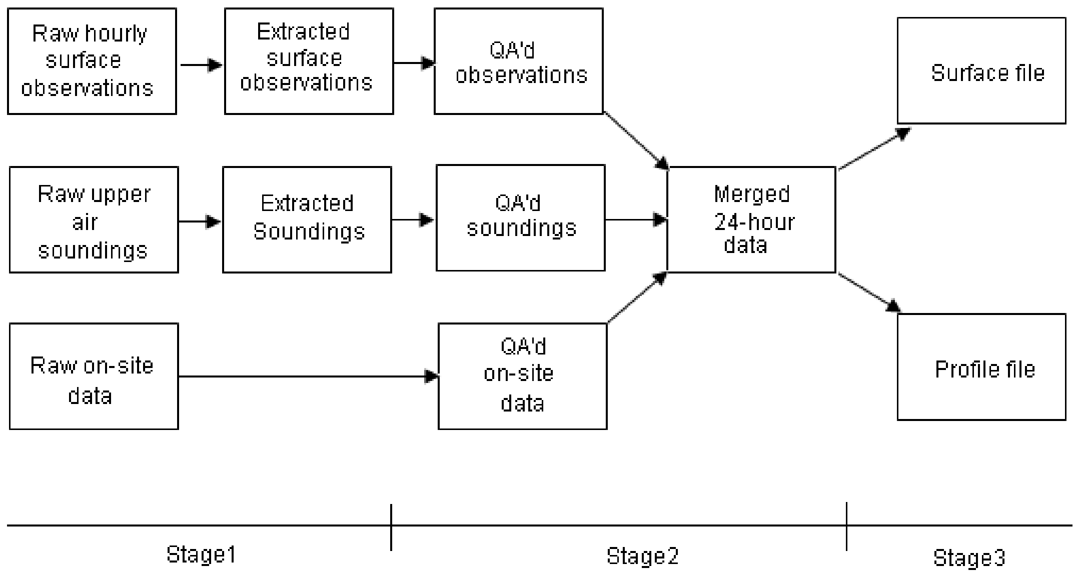


Figure 2.3 AERMET processing stages (adapted from USEPA, 2004a)

2.2.3.2 CALPUFF

CALPUFF has been accepted by the U.S. EPA as a preferred model for regulatory applications from April, 2003 (New Zealand National Institute of Water and Atmospheric Research, 2004). It consists of three main components: CALMET, CALPUFF*, and CALPOST. CALMET is a meteorological processor that develops hourly wind and temperature fields in the three-dimensional gridded modeling domain; CALPUFF* is a transport and dispersion processor that simulates dispersion and transformation processes of pollutant(s) along the dispersion way; CALPOST is a postprocessor used to process the files from CALPUFF to produce a summary of the simulation results (USEPA, 1998).

CALPUFF is a Lagrangian puff dispersion model that is able to simulate the effects of complex meteorological condition in the process of pollutant transport (Scire, 2000). This model can handle emissions from any types of sources including point, line, area, and volume sources. Both gridded receptors and discrete receptors can be accepted in one run time. It could be driven by either complicated three-dimensional meteorological data provided by CALMET for a full run or simple meteorological data from a single weather observation tower just as used by AUSPLUME or ISCST3 for a simple simulation purpose. The model contains algorithms for near-source effects such as building downwash, partial plume penetration, sub-grid scale interactions as well as longer-range effects as pollutant removal, chemical transformation. Best performance of CALPUFF usually depends on high quality of meteorological data (USEPA, 1998).

To run the CALPUFF dispersion model, software CALPUFF* and CALPOST must be run in sequence. CALPUFF* is a Graphical User Interface (GUI) used to yield a binary file to be used in CALPOST. Inputs of CALPUFF* includes nine parts: Run information, Grid setting, Species, Chemical Transformation Method, Deposition, Model Options, Sources, Receptors, and Output. All these nine parts above must be filled before a successful run. CALPOST can refine and prepare the output of CALPUFF* in certain formats for some specific purposes, e.g., it can produce odour concentration data in the format ready for drawing graphics or list four top concentration values at each odour receptor. Meteorological data involved in the part "Model Option" in CALPUFF* could be prepared by CALMET or ISC ASCII file. The method how meteorological data were produced by CALMET has been addressed previously in the chapter of AERMOD description. Meteorological data yielded by ISC ASCII file were produced by filling meteorological parameters in a text editor in a specific format.

Odour emissions were originally treated as integrated puffs by CALPUFF* when it was developed; however, it was realized later that use of the integrated puff approach was inefficient as new features were added to the model for handling local-scale applications. Subsequently, a more efficient approach of treating the emissions as slugs was developed. It was proposed to use when local conditions like local meteorological condition and/or terrain situation were complicated (USEPA, 1998).

2.2.4 Sensitivity Analysis and Evaluation of Air Dispersion Models

Sensitivity analysis of the models is used to find out the impact of input parameters on the output of the models. Literature review results showed most of the sensitivity analysis were conducted to find out the impact of climatic parameters on the odour dispersion. Evaluation of models aimed at giving the models users the confidence when using these models. Evaluation was conducted by comparing modeled and field measured odour occurrences to find the agreement of them.

2.2.4.1 Sensitivity Analysis of Air Dispersion Models

Sensitivity analysis of air dispersion models is the analysis conducted to find out the output variation of air dispersion models following the change of input parameters. Air dispersion models contain a lot of input parameters, e.g., odour emission rate, climatic condition, topography. Climatic condition is a very important one among these parameters, because it is changeable and has great impact on odour dispersion in atmosphere. The input climatic data of air dispersion models consists of mixing height, ambient temperature, atmospheric stability class, wind speed, and wind direction. Climatic parameter sensitivity analysis is an useful tool not only in identifying important parameters of their impact on downwind odour concentration value but also in identifying areas where further research will be most productive (Ould-Dada, 2008).

Smith (1993) carried out the sensitivity analysis of the STINK model to meteorological condition when predicting downwind odour concentrations from a ground-level agricultural odour source.

It was found that wind speed was a very important factor that affects odour dispersion and, the change of the atmospheric stability class by one class interval to the next more stable class involved the increase in concentration of between 40 and 90%. However, wind direction was just moderately important. Chastain and Wolak (1999) used a windows-based computer program based on Gaussian plume dispersion equations to conduct the climatic sensitivity analysis in modeling livestock odour dispersion. Results showed that the odour plume was wider and longer under stable weather conditions during the day, presenting the most critical period for odour problems. It was also found that for the atmospheric stability condition, which could be generally determined by Pasquill stability classes, odour would travel shorter distance under relatively unstable atmospheric stability conditions (A and B), and longer distance under stable atmospheric conditions (F and G). Jacobson et al. (2000) and Guo et al. (2001a) validated INPUFF-2 and found weather condition had a substantial impact on odour dispersion. For the same wind speed, the maximum odour travel distance decreased sharply if stability classes changed from unstable to stable. For the same stability class, the maximum odour travel distance decreased greatly if wind speed increased. Unfortunately, the effect of other parameters on this model was not analyzed. Ferenczi (2005) conducted sensitivity analysis of RIMPUFF model (a kind of mesoscale puff model) before using it to conduct actual odour dispersion simulation. It was found in that article for more stable atmosphere and lower wind speed the odour plume covered smaller area but the concentration of contamination over this area was much higher compared with the unstable atmosphere and high wind. It was also found decreasing values of mixing height made the concentration values higher and higher in every stability class from A to F and the difference between the maximum and minimum concentration was the largest in stability class F, and smallest in stability class A. Xing et al. (2007) conducted sensitivity of ISCST3, AUSPLUME, CALPUFF, and INPUFF-2 under steady-state weather conditions. It was concluded wind speed had great impact on all four models. Under stability class E, when the wind speed increased from 1 to 5 m/s, the maximum odour travel distance (distance where odour concentration was 10 OU/m^3) decrement range was 70 to 79% for four models. This trend happened under all other stability classes. It was also found the influence of atmospheric stability class at models was huge. As the stability class changed from F to E under wind speed of 3 m/s, the change range of maximum odour travel distance for four models was 32 to 57%. For the same wind speed, the difference of models' output increased if stability class interval increased. It was also detected ambient temperature had some impact on INPUFF-2 but its impact was very limited on other models; however, wind direction had some impact on all four models near the swine farm, and this impact faded away when the distance increased.

2.2.4.2 Evaluation of Air Dispersion Models

Air dispersion models should be evaluated in prior to application in a practical odour dispersion simulation. Only after verifying them, can we have the confidence to use them. Evaluation was carried out through comparing models predictions with field measurements. Field measurements were deemed as standard values and, modeled results are then compared with corresponding standard values to check if they agree with each other.

Capability of various air dispersion models in terms of predicting odour concentration downwind agricultural odour sources has been studied by many researchers. Zhu et al. (1999) evaluated INPUFF-2 in predicting downwind odours from several animal production facilities. According to the Wilcoxon Signed Rank Test, the model was able to predict the downwind odour levels at distances of 100, 200, and 300 m from odour sources with confidence of 95, 92, and 81%, respectively. At farther distances, such as 400 and 500 m, the accuracy of prediction of this model was significantly reduced. Guo et al. (2001a) calibrated the same model for long-distance odour dispersion estimation. This research was carried out on a 4.8 by 4.8 km grid of farmland containing 20 livestock/poultry farms. The comparison between the modeled and measured odour intensities indicated that the model could successfully estimate odour intensity 1 (faint odour) traveling up to 3.2 km under stable atmospheric conditions ($P > 0.05$). However, the model underestimated moderate to strong or very strong odours and odours that occurred during neutral or unstable weather as compared with the field measured data ($P < 0.05$). The overall percentage of agreement was 81.8%. Walker et al. (2002) compared the outputs of models ISCST3, CALPUFF, and AERMOD as applied in gas concentrations prediction in 48-hour period of time around a plant located in Nova Scotia, Canada and found CALPUFF yielded the best outcome for large simulation domain of 400 by 600 km followed by AERMOD, however, AERMOD behaved better than CALPUFF in small area of 25 by 25 km. ISCST3 did not produce good results as AERMOD or CALPUFF. Koppolu et al. (2002) assessed AERMOD and STINK in predicting odour concentrations downwind a ground-level area source in two experiments. Both of the experiments showed both models performed quite well generally. In the worst case, the average of predicted concentrations was 24 percent greater than the measured ones. Different averaging times of meteorological data were also tested for AERMOD. It was concluded that short time interval (15 and 30 minutes) instead of 1-hr as the standard averaging time was more suitable for AERMOD if the wind direction and wind speed were in great variation. Zhou et al. (2005) evaluated three dispersion models for livestock odour dispersion, i.e., ISCST3, INPUFF-2, and AUSPLUME, and the results showed they all can predict downwind odour concentrations with good agreement for distances of 500 and 1000 m but pretty poor at 100 m. Xing, (2006) evaluated four models, i.e., AUSPLUME, ISCST3, CALPUFF, and INPUFF-2 using field measured odour plume data from University of Minnesota, University of Saskatchewan and University of Manitoba. It was found for the overall agreement level, INPUFF-2 achieved the best agreement (60%) of model predicted and field measured odour concentration for the odour data from University of Manitoba followed by CALPUFF (56%). For odour measurement data from University of Minnesota, CALPUFF achieved the best agreement (44%) followed by INPUFF-2 (31%) for the overall agreement. When it came to using the odour measurement from University of Saskatchewan, again INPUFF-2 and CALPUFF got top two places of the agreement of predicted and measured odour intensities in four models with the agreement was 52 and 81%, respectively. Schmidt and Jacobson (2006) used AERMOD and

CALPUFF to predict ambient hydrogen sulfide concentrations near a 2000 head finishing site in Minnesota over five consecutive years. The results indicated predicted property line setback distances using AERMOD were greater than those distances predicted by CALPUFF; however, there was also variability between geographic locations, and different simulation times. Curran et al. (2007) presented an evaluation of ISC3 and CALPUFF for the prediction of odour concentrations at a commercial pig unit. The results turned out that the predicted odour concentrations of both models were pretty close. The ratio of the average predicted to mean measured concentration changed from 1.40 to 9.37. Over 80 percent of the predictions were greater than the corresponding measured values, indicating that these two models yielded over-predicted estimates of downwind odour concentration. The huge variation between model predicted and measured odour concentrations may direct the need of “scaling factor”, which will be addressed in details in chapter 5.3.3.

2.2.5 Application of Air Dispersion Models in Determining Odour Setback Distance

As stated previously, determination of odour setback distance from animal production sites can be achieved by established odour control guidelines or air dispersion models. The guideline approach primarily uses empirical formulae and/or equations to calculate appropriate setbacks. However, the second method uses mathematical air dispersion models to predict odour concentrations downwind odour sources. With the predicted odour concentrations and pre-determined acceptable odour criteria, the acceptable setback distance could then be determined.

The guideline method can be categorized into two groups: land use/zoning guideline and parametrically determined guideline. Land use/zoning guideline recommend the use of fixed-distance setbacks that are primarily based on land use or zoning criteria. This method could be found in "Control of Manure Odours" in ASAE, (1994); Miner and Barth, (1988) and Sweeten, (1998). This kind of guideline has been applied in US, Australia and, Canada (Jacobson et al., 2002). The second guideline approach first accesses the information of the odour source and then calculates the setbacks using an empirical model and finally modifies the setback distance according to the land use categories. The currently used parametrically determined guidelines are: MDS-Π model (Fraser, 2001; OMAFRA, 1995), Warren Spring model (Williams and Thompson, 1986), Austrian model (Schauberger and Piringer, 1997), and Purdue model (Lim et al., 2000). Parametrically determined guidelines are used in Austria, Germany, The Netherlands, Switzerland, and the U.K. (Jacobson et al., 2002).

Right now the only used air dispersion model in predicting odour setback distance is the Minnesota Odour from Feedlots Setback Estimation Tool (OFFSET) model. The OFFSET model has been developed based on numerous odour emission measurements, a dispersion model (INPUFF-2), and historical Minnesota weather data. The setback distances are determined by different odour concentration levels together with the desired odour "annoyance free" frequency (91 to 99%). This model has been validated by Jacobson, et al. (2000), Zhu et al. (1999 and 2000), and Guo et al. (2001a).

2.3 Summary

Factors influence agricultural odour dispersion should be carefully considered when studying odours related issues. For those researchers who use air dispersion models to predict odour concentrations around the odour source, being familiar the relationship between the model output and these factors can make the researchers know if the modeled results are right or not compared with the other results. Sensitivity analysis can provide us an opportunity to know how and the extent of model's input affects the output, and whether the model's output makes sense following the change of the inputs. Limited information could be found in literatures regarding analysis of models' sensitivity to their inputs, especially climatic parameters, of CALPUFF and AERMOD; however, it will be conducted in this project.

Evaluation of models is a necessary step before putting them into odour concentration prediction. A lot of researches have been carried out to evaluate the performance of widely used air dispersion models; however, model evaluation outcomes for different researchers presented very different results. There are no an agreement among these researchers that a certain model is a better than the others in all situations. Furthermore, although evaluation of CALPUFF and AERMOD could be found in literature, not so much work of comparison between them can be observed. CALPUFF's performance in odour dispersion simulation has been proved to be good by a lot of researchers as stated previously, so comparison between CALPUFF and AERMOD could provide a chance to know AERMOD's performance in odour dispersion simulation. With accessibility to original field measured odour data from University of Minnesota and University of Alberta during the past few years, we can evaluate and compare AERMOD and CALPUFF more confidently.

Almost all of the odour setback distance was determined by odour control guidelines. These guidelines were followed by governments in Canada to make decisions involved in construction and expanding of the animal production sites. Using of air dispersion models, which are based on scientific calculation, is a promising way in predicting odour setback distance. Science-based odour setback distance predicted by air dispersion models will be provided in this project to compare with odour control guidelines, making the setbacks more convictive.

3. OBJECTIVES

The overall goals of this project are to conduct sensitivity analysis of AERMOD and CALPUFF to major climatic parameter, to evaluate the performance of these two air dispersion models for livestock odour prediction, and to evaluate the validity of setback guidelines set by Canadian Prairie Provinces against the predictions of air dispersion models. To achieve these goals, the following objectives will be needed to be fulfilled:

1. To conduct sensitivity analysis of these two models to major climatic parameters to reveal the impact of these climatic parameters on odour dispersion;
2. To evaluate the performance of these two models with available odour plume data measured by trained odour sniffers or resident-odour-observers of University of Minnesota and University of Alberta;
3. To make predictions of science-based setback distance with acceptable odour concentration utilizing a better model in these two and hourly historical weather data for typical sized swine farms in Saskatchewan, Canada;
4. To compare the setback distance predicted by the selected model with guidelines/models recommended setback distance of Prairie Provinces in Canada.

Chapter 4 is to be served to fulfill objective 1 of model sensitivity analysis. Chapter 5 and 6 will be involved in performance evaluation of these two models using field odour measurement data from University of Minnesota and University of Alberta, respectively. Chapter 7 aims at fulfill objectives of 3 and 4. Finally, a summary of conclusions and recommendations for future studies will be given at chapter 8.

4. SENSITIVITY ANALYSIS OF AERMOD AND CALPUFF TO MAJOR CLIMATIC PARAMETERS FOR SWINE ODOUR DISPERSION

4.1 Introduction

Sensitivity analysis of air dispersion models to input parameters, especially climatic parameters, was carried out to find the variation of models output, i.e., variation of maximum odour travel distance and odour concentrations within 5 km from the odour source, to input parameters. Climatic parameters as input of air dispersion models generally include mixing height, ambient temperature, atmospheric stability class, wind speed, wind direction, solar radiation, and relative humidity. However, five major climatic parameters, i.e., mixing height, ambient temperature, atmospheric stability class, wind speed, and wind direction were the involved meteorological parameters in two models, CALPUFF and AERMOD, for this project purpose.

Sensitivity analysis of air dispersion models was conducted under both steady-state and variable weather conditions by researchers. Under steady-state weather condition, it was carried out by changing the value of one climatic parameter while keep other climatic parameters constant to find out how the models' output changes following the change of this parameter. Under variable weather conditions, all the climatic parameters changed at the same time, the output changed following the change of these parameters. In this part of the project, the author will analyze the sensitivity of CALPUFF and AERMOD to the input meteorological parameters and then compare the predicted values between them.

4.2 Materials and Methods

Sensitivity analysis of models was also conducted under both steady-state and variable weather conditions in this part of the project. Under steady-state weather condition, influence of five major climatic premasters, i.e., mixing height, ambient temperature, stability class, wind speed, and wind direction, at maximum odour travel distance and odour concentrations within 5 km from the source as predicted by models were analyzed. Under variable weather condition, year of 2003 annual hourly meteorological data were employed to get maximum odour travel distance for odour concentrations of 1, 2, 5 and 10 OU/m^3.

4.2.1 Site Description and Odour Emissions

For the purpose of conducting model sensitivity to some major climatic parameters, a swine farm with location of 113.82W (Longitude), 53.31N (Latitude) and elevation of 715 m above mean sea level (MSL) in Calmar, Alberta, Canada was selected to get the odour emission rates. This farm consisted of one barn and two uncovered EMS cells. The relative position of the barn and the manure cells is sketched in Figure 4.1. The farm was surrounded by flat rural crop field. The odour emissions from the barn and the EMS cells used in this part are listed in Table 4.1.

Table 4.1 Odour emission rate from barn and manure storages

Source	Total odour emissions (OU/s)	Area (m^2)	Odour emission rate (OU/s-m^2)
Barn	437,928	32*	13685.25**
Cell 1	270,537	5625	48.1
Cell 2	325,944	9801	33.26

*The barn is treated as 32 separated points representing the whole area of the barn;
**The odour emission rate from the barn represents the emission rate of each point.

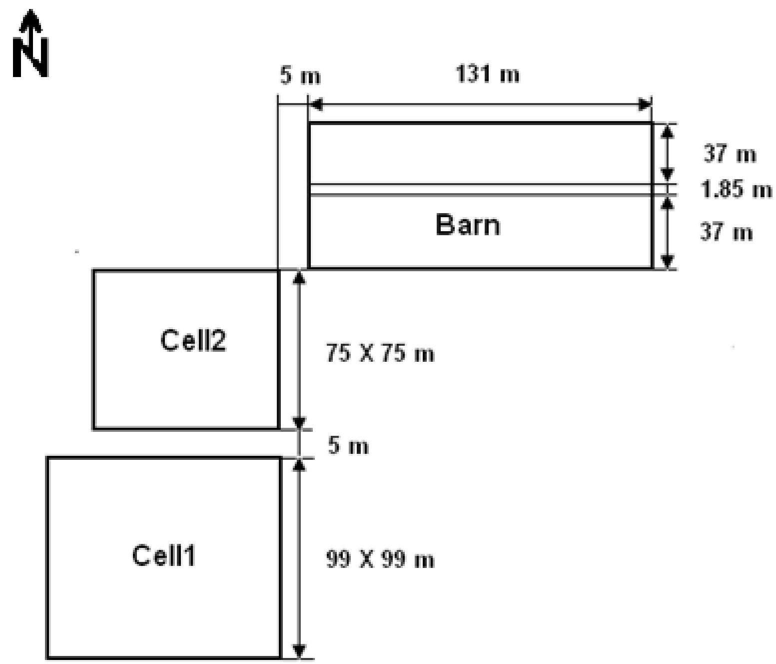


Figure 4.1 Layout of the swine barn for the purpose of conducting sensitivity analysis

4.2.2 Meteorological Conditions

Both steady-state and variable meteorological conditions were used to evaluate the sensitivities of these two models as impacted by five major climatic parameters and the predicted differences between them under the same weather condition will also be revealed. As steady-state meteorological condition which is in favor of odour transportation can bring in high odour concentrations downwind odour sources, this kind of weather condition is always in researchers' minds to carry out model sensitivity analysis. Steady-state climatic weather condition involved in this part can be divided into following categories grouped by several atmospheric stability classes together with different wind speeds:

F3 and F2: Atmospheric stability F (moderately stable) with wind speed of 3 and 2 m/s;

E5, E4, E3 and E2: Atmospheric stability E (slightly stable) with wind speed of 5, 4, 3 and 2 m/s;

D15, D8, D6, D5, D4, D3, D2 and D1: Atmospheric stability D (neutral) with wind speed of 15, 8, 6, 5, 4, 3, 2 and 1 m/s; and

C5: Atmospheric stability C (slightly unstable) with wind speed of 5 m/s.

It needs to be pointed out that though Pasquill stability class is used by most of the models to express the weather condition; it is not one of the input climatic parameters of AERMOD. However, Pasquill stability class can be determined by solar radiation (*R*) and wind speed at daytime, or cloudiness (*n*) and wind speed at nighttime (Table 4.2). Cloudiness is an input parameter of AERMOD. Relationship between *n, R,* and R_0 (clear sky solar radiation) is shown as following (Allen et al., 2006):

$$R = R_0\ (1 - 0.75n^{3.4}) \qquad (4.1)$$

The value of R_0 is constant for one place on the earth if the date and time and location are specified. For the selected date and time (12:00 AM, June, 21st, 2003) of the study area, the value of R_0 was 845.22 W/m^2. The value of *R* can be calculated out according to equation 4.1 if the value of *n* is given.

Table 4.2 Turner's method for estimating stability class (Turner, 1970)

Wind speed(m/s)	Day time solar radiation (R) (W/m^2)				Night time Cloudiness(n)	
	⩾ 925	925 - 675	675 - 175	< 175	>= 4/8	<= 3/8
< 2	A	A	B	D	—	—
2 - 3	A	B	C	D	E	F
3 - 5	B	B	C	D	D	E
5 - 6	C	C	D	D	D	D
>= 6	C	D	D	D	D	D

As stated previously, Albedo, Bowen ratio, and surface roughness length were used to in AERMOD to characterize the meteorological condition of atmosphere. The values of these three parameters proposed by the US EPA for use of AERMOD are presented in Tables 4.3 to 4.5.

Table 4.3 Albedo of ground covers by land-use and season (USEPA, 2000)

Land-use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.12	0.10	0.14	0.20
Deciduous Forest	0.12	0.12	0.12	0.50
Coniferous Forest	0.12	0.12	0.12	0.35
Swamp	0.12	0.14	0.16	0.30
Cultivated Land	0.14	0.20	0.18	0.60
Grassland	0.18	0.18	0.20	0.60
Urban	0.14	0.16	0.18	0.35
Desert Shrub land	0.30	0.28	0.28	0.45

Table 4.4 Bowen ratio by land-use and season (average moisture conditions) (USEPA, 2000)

Land-use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.1	0.1	0.1	1.5
Deciduous Forest	0.7	0.3	1.0	1.5
Coniferous Forest	0.7	0.3	0.8	1.5
Swamp	0.1	0.1	0.1	1.5
Cultivated Land	0.3	0.5	0.7	1.5
Grassland	0.4	0.8	1.0	1.5
Urban	1.0	2.0	2.0	1.5
Desert Shrub land	3.0	4.0	6.0	6.0

Table 4.5 Surface roughness length by land-use and season (in meters) (USEPA, 2000)

Land-use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.0001	0.0001	0.0001	0.0001
Deciduous Forest	1.00	1.30	0.80	0.50
Coniferous Forest	1.30	1.30	1.30	1.30
Swamp	0.20	0.20	0.20	0.20
Cultivated Land	0.03	0.20	0.05	0.01
Grassland	0.05	0.10	0.01	0.001
Urban	1.00	1.00	1.00	1.00
Desert Shrub land	0.30	0.30	0.30	0.15

To conduct sensitivity analysis under variable meteorological condition, 2003 annual hourly meteorological data of the study area were used to get the annual average odour concentrations in the vicinity of the selected farm. As it was stated previously, both of surface and upper air meteorological data are needed to run AERMOD, the surface meteorological data could be obtained easily for the modeled place while the upper air data could only be acquired from the nearest upper air station, Stony Plain Upper Air Station, Edmonton, which is 32.6 km away from the farm site.

4.2.3 Computation Assumptions

Because actual meteorological condition is changeable and complicated, we only consider the most common situations. Some computation assumptions were assumed during the process of using the models under steady-state meteorological conditions:

1. For usage of these two models, the barn was deemed as 32 point sources to represent the shape of the barn, and the emitting rate of every point is the same. The cells were treated as area sources. The odour emitting height of the barn and the earthen manure storage cells was 1.5 and 0 m, respectively;
2. Odour emission rates from the barn and the earthen manure storage cells listed in Table 4.1 were treated as constant as we only considered the effect of climatic weather conditions on the models prediction not the odour emission rate;
3. Odour exit velocity from the barn was set to be 0.05 m/s because it was treated as a batch of point sources instead of fans, and the exit velocity from the earthen manure storage cells was set to be 0.05 m/s, too;
4. For the barn, the exhaust air temperature was assumed to be 20 ^{o}C when ambient temperature ranged from -30 to 20 ^{o}C and 3 ^{o}C above the ambient temperature when the

ambient temperature was higher than 20 ^{o}C. The odour exit temperature of earthen manure storage cells was set to be the same as ambient air temperature;

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. Odour receptors' detection height was considered as 1.5 m above the ground because the height of field odour sniffers' noses was approximately 1.5 m high;
7. Wind speed and direction were deemed to be both horizontally homogeneous in the scope of the field selected to carry out the study;
8. The prevailing wind direction of the examined area of NNW (north-northwest) was chosen as the wind blowing direction when conducting simulation except for the analysis of various wind directions;
9. Only odour concentration was tested in the study which means deposition and chemical transformation were not considered during all the simulations.

Under steady-state weather condition, the critical odour detection distance (CDD) and odour concentrations within 5 km from the odour source predicted by the two models were examined and predictions between two models were also compared. Critical odour detection distance was defined as the maximum odour travel distance from the odour source to the location of the odour receptor where centerline odour concentration was reduced to 10 OU m^{-3}. Because the distance of interest for setback determination was within 5 km from the odour source (Guo et al., 2004b), odour concentrations within this range were examined. Odour concentrations were also compared at different distances to the odour source within 5 km between two models. Under variable weather condition, maximum odour travel distance with odour concentrations of 1, 2, 5 and 10 OU/m^3 were examined in this area.

4.2.4 Model Configuration

CALPUFF of version 5.7 and AERMOD of version 02222 were used in this part. Variables/parameters were specified according to the sensitivity analysis simulation conditions in this part.

4.2.4.1 CALPUFF Configuration

Inputs of CALPUFF were broadly divided to odour emission rates, meteorological data, terrain condition, location of receptors, some other dispersion simulation options, as well as output specifications.

As stated previously, the barn was divided to 32-point odour sources to represent the shape of the barn. These 32 points covered the whole area of the barn except for the aisle. The two manure storage cells were treated as area sources. Odour emission rates from these point and area sources were listed in Table 4.1. The dimension of three odour sources was sketched in Figure 4.1.

Sensitivity analysis of models were conducted under both steady-state and variable weather conditions. Under steady-state weather condition, values of parameters of mixing height, ambient temperature, atmospheric stability, wind speed, and wind direction were addressed in details in chapter 4.3 at the beginning of each subchapter. Under variable weather condition, 2003 hourly meteorological data from the first hour to the last hour of this year were employed. Meteorological data were stored in the certain format in a text editor (ASCII file) that CALPUFF* can accept.

The main parameters used in CALPUFF* to specify the terrain condition were landuse type, and surface roughness length. The landuse type of the simulated area was deemed as unirrigated agricultural land based on the land condition in this area and the surface roughness length corresponding to this kind of land was set to 0.20 according to Table 4.4 at the simulated time period.

Odour receptors were located in the field of 20 by 20 km with the centroid of all three odour sources approximately in the center. The location of the centroid was calculated out based on the location of the center of each odour source and the corresponding odour emission rate. The gridded spacing of neighbouring receptors was 50 m, i.e., a total of 160,000 receptors.

Some other dispersion simulation options were specified as the following:

a) The ODOUR is the only simulated species in this project, and other species like SO_X, NO_X, etc. were not considered here;
b) No chemical transformation was considered here because it was too complicated to take in account of chemical transformation of these species;
c) Neither dry deposition nor wet deposition was considered in this part;
d) Regarding the plume rise method, only transitional plume rise was considered, others like stack downwash, vertical wind shear above stack top etc. were not considered based on the characteristics of the agricultural odour dispersion process;
e) Treating odour plume as puff not slug;
f) Because this area was pretty flat, no effect of terrain was considered when considering effect of terrain on odour dispersion.

When running CALPUFF*, the output was a binary file. This file was used as the input of CALPOST to get the final desired output, i.e., an ASCII file containing odour concentration (OU/m^3) at each odour receptor. The detailed information of run-stream screen of CALPUFF version 5.7 was presented in Appendix A.

4.2.4.2 AERMOD Configuration

AERMOD employed a totally different approach to type in inputs of this model compared with CALPUFF. It used text editor not GUI screen to edit the run-stream file. However, the AERMOD run-stream file also contained approximately the same information as CALPUFF to yield the final output, which included odour emission rates, meteorological data, location of receptors, as well as output specifications. The effect of terrain on odour dispersion had already been considered in AERMET, the preprocessor of AERMOD to produce meteorological data to be used in AERMOD.

The information of odour emission rates were the same as those described in the chapter of CALPUFF configuration above.

Both steady-state and variable weather data were used by AERMOD to carry out sensitivity analysis as that in CALPUFF. The weather condition parameters described in details in chapter 4.3 Results and Discussion, equation 4.1 and Table 4.2 were applied to relate the wind speed, solar radiation, and atmospheric stability class. Values of albedo, Bowen ratio, and surface roughness length used in AERMET were chosen according to Tables 4.3 to 4.5 Based on the simulated season in the year. According to those tables, Albedo, Bowen ratio, and surface roughness was set to 0.14, 0.3, and 0.03 in spring; 0.20, 0.5, and 0.20 in summer; 0.18, 0.7, and 0.05 in fall; and 0.60, 1.5, and 0.01 in winter, respectively.

Detailed information of the odour receptors was the same as that addressed in CALPUFF configuration above.

When running AERMET, the outputs were surface and profile file. These files were used as the input of AERMOD to get the final desired output, i.e., an ASCII file containing odour concentration (OU/m^3) at each odour receptor. The detailed information of run-stream files of AERMOD Version 02222 was presented in Appendix B.

4.3 Results and Discussion

Sensitivity analysis results of AERMOD and CALPUFF to five major climatic parameters under steady-state weather conditions and maximum odour travel distance with odour concentrations of 1, 2, 5, and 10 OU/m^3 under variable weather conditions were addressed in details in this part. At the same time, discussions of the simulated results were also made.

4.3.1 Mixing Height

The mixing height or mixing depth is the height from ground to space where turbulent mixing of vertical and horizontal air happens. When conducting model's sensitivity to this factor, other factors were not changed. Mixing height was set to values of 100, 200, 500, 1500, 3000 and 5000 m based on the statistical result of year 2003 hourly weather data of this area that the minimum and maximum mixing was around 80 and 4700 m respectively. The combinations of stability class and wind speed were: C5, D1, D8, E1, E3 and F3. Ambient temperature was set to 20 ^oC, and prevailing wind direction of NNW was selected.

The simulation results showed under all weather conditions, mixing height had no impact on model predictions for both AERMOD and CALPUFF when the mixing height was set to 100, 200, 500, 1500, 3000 and 5000 m. We may find the reason in the "fact" that the agricultural odours normally transport just a few meters above ground, hence the name ground-level odours. Because mixing height has no impact on simulation results, a value of 1500 m was used when conducting sensitivity analysis of other parameters.

4.3.2 Ambient Temperature

The impact of different ambient temperatures on odour dispersion was simulated when ambient temperature was in the range of -20 ^oC to 30 ^oC (temperature range of the involved area was -37 to 34 ^oC of year 2003) with constant of 5 ^oC. Prevailing wind direction of NNW as well as mixing height of 1500 m was chosen. The combinations of stability class and wind speed were: C5, D3, E5 and F3.

4.3.2.1 Impact on Critical Odour Detection Distance

Figure 4.2 shows the CDD as simulated by two models under C5, D3, E5 and F3. It shows ambient temperature has no effect on CDD for both AERMOD and CALPUFF when the weather conditions were C5 and D3. However, it has some influences at CALPUFF's predictions under weather conditions E5 and F3. Under E5 and F3, the CDD increased from 2.4 to 2.7 km and 7 to 7.5 km, or say increased by 11 and 7%, respectively. Ambient temperature still had no or very limited impact on AERMOD under these two weather conditions. Based on this result, AERMOD was not sensitive to the normal ambient temperature in terms of the CDD; while for CALPUFF, the effect was also very limited. The difference of CDD under C5, D3, E5 and F3 between two models (with AERMOD the base) was -13, 60, 200 - 238 and 204 - 257%. It can be observed difference increased following the change of stability class to the next more stable one.

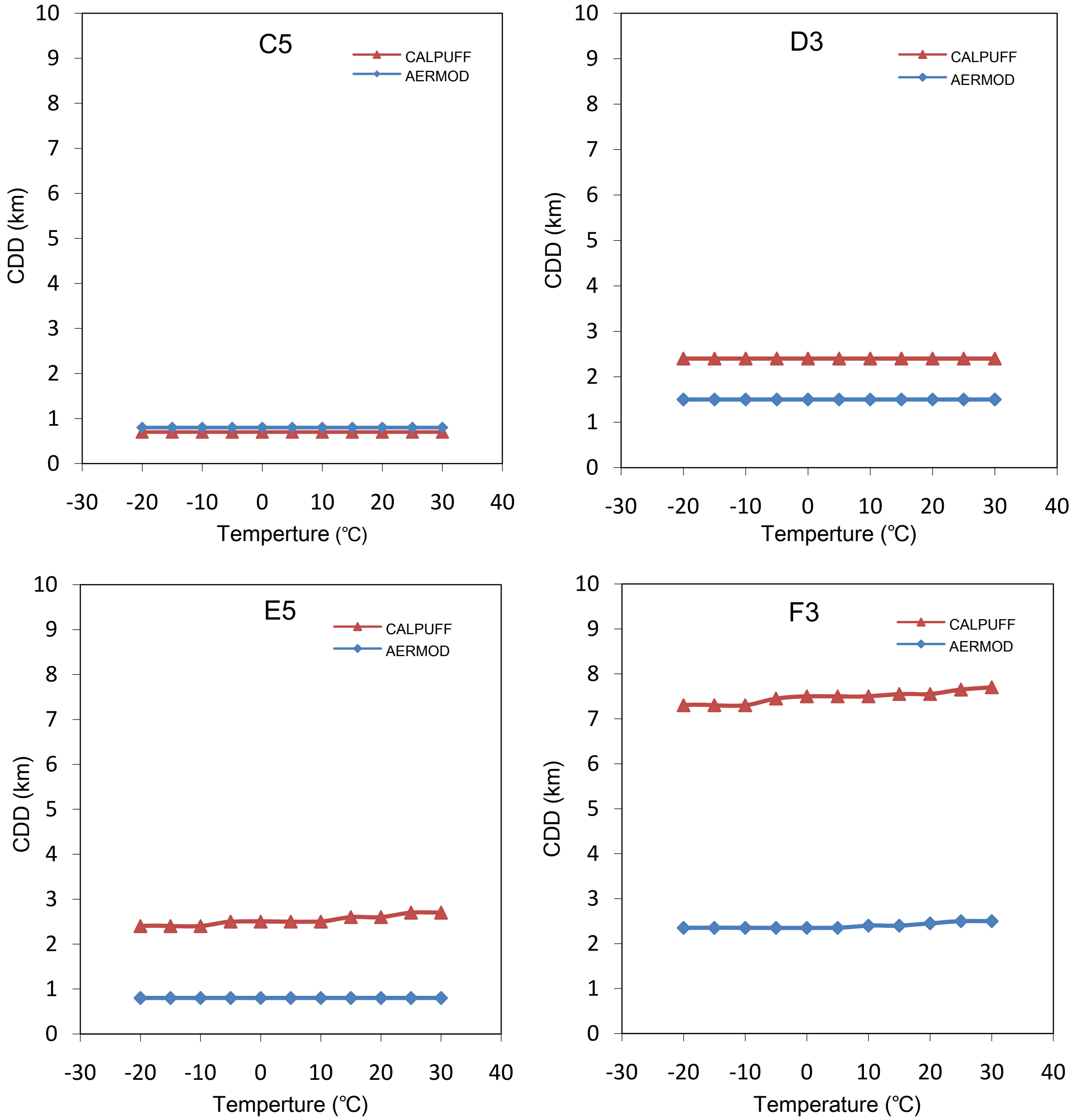


Figure 4.2 Impact of ambient temperature on CDD

4.3.2.2 Impact on Odour Concentrations within 5 km

The predicted centerline concentrations of odour plume in 5 km from the odour source under C5, D3, E5 and F3 are given in Tables 4.3 to 4.6. From these tables a trend can be observed the odour concentration increased with the increases of ambient temperature at the same distance for CALPUFF. For example, when temperature increased from -20 to 30 ^{o}C under C5, odour concentration increment was 51.5 and 46.2% at distance of 0.2 km, and 34.5 and 17.9% at distance of 0.3 km for CALPUFF and AERMOD, respectively. The reason of odour traveled longer distance when temperature increased was that with increase of temperature, more odour molecules moved into the odour transporting direction, bringing higher odour concentration. It could also be observed the differences are significant at close distance to the source for both models under all weather conditions, but the differences faded away with the increase of distance and disappeared or were very limited under all selected weather conditions at distance of 5 km. This could tell us impact of temperature was evident at close distance to the odour source.

Table 4.3 Centerline concentrations of odour plume under C5 (OU/m^3)

Model	Temperature (℃)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	-20	33	29	15	13	7	4	3	2	1	1	1	1	1
	-10	33	32	15	13	7	4	3	2	1	1	1	1	1
	0	37	34	15	13	7	4	3	2	1	1	1	1	1
	10	42	37	15	13	7	4	3	2	1	1	1	1	1
	20	48	39	15	13	7	4	3	2	1	1	1	1	1
	30	50	39	15	13	7	4	3	2	1	1	1	1	1
AERMOD	-20	39	28	20	17	8	5	3	2	2	2	1	1	1
	-10	44	28	20	17	8	5	3	2	2	2	1	1	1
	0	53	28	20	16	8	5	3	2	2	1	1	1	1
	10	54	29	20	18	8	5	3	2	2	1	1	1	1
	20	57	30	21	18	8	5	3	3	2	2	1	1	1
	30	57	33	22	19	8	5	4	3	2	2	1	1	1

Table 4.4 Centerline concentrations of odour plume under D3 (OU/m^3)

Model	Temperature (℃)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	-20	87	64	43	36	23	17	12	10	8	6	5	4	4
	-10	87	64	44	36	23	17	13	10	8	6	5	4	4
	0	87	64	44	37	23	17	13	10	8	6	5	4	4
	10	87	86	44	37	24	17	13	10	8	6	5	4	4
	20	114	120	44	37	24	18	13	10	8	6	5	4	4
	30	123	126	44	37	24	18	13	10	8	6	5	4	4
AERMOD	-20	74	43	31	27	16	10	7	5	4	3	3	2	2
	-10	74	43	32	28	16	10	7	5	4	3	3	2	2
	0	75	44	34	30	16	10	7	5	4	3	3	2	2
	10	79	46	36	32	16	10	7	5	4	3	3	2	2
	20	97	49	38	32	16	10	7	5	4	3	3	2	2
	30	104	64	42	36	16	10	7	6	4	4	3	3	2

Table 4.5 Centerline concentrations of odour plume under E5 (OU/m^3)

Model	Temperature (℃)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	-20	71	56	40	33	19	15	12	10	8	7	6	5	5
	-10	71	56	40	33	19	15	12	10	8	7	6	5	5
	0	71	56	40	33	19	15	12	10	8	7	6	5	5
	10	71	56	40	33	20	16	13	10	9	7	6	5	5
	20	71	61	40	33	20	16	13	11	9	7	6	5	5
	30	98	110	40	33	21	17	13	11	9	7	6	5	5
AERMOD	-20	39	28	21	17	9	5	4	3	2	2	1	1	1
	-10	44	28	21	17	8	5	3	3	2	2	1	1	1
	0	51	29	21	17	8	5	3	3	2	2	1	1	1
	10	55	29	22	18	8	5	3	3	2	2	1	1	1
	20	58	31	23	19	8	5	4	3	2	2	1	1	1
	30	58	34	25	21	8	5	4	3	2	2	2	1	1

Table 4.6 Centerline concentrations of odour plume under F3 (OU/m^3)

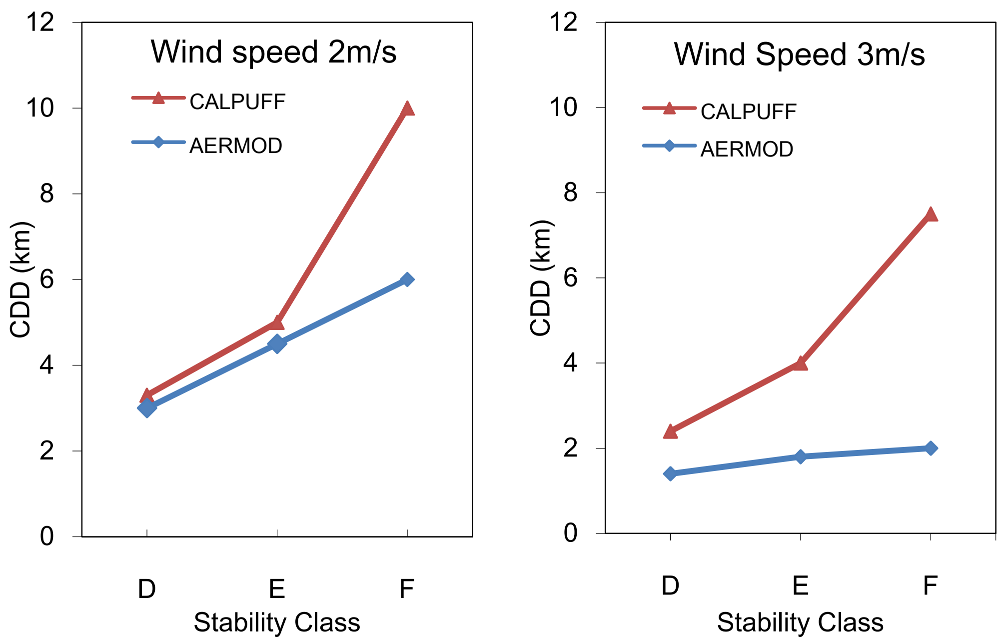
Model	Temperature (℃)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	-20	173	144	109	91	50	37	31	27	24	21	19	17	15
	-10	173	144	109	91	50	37	32	28	24	22	19	17	16
	0	173	144	109	91	50	38	32	28	25	22	20	18	16
	10	173	144	109	91	51	39	33	29	26	23	20	18	16
	20	173	144	109	91	51	40	35	31	27	24	21	19	17
	30	230	275	109	91	52	42	36	32	28	25	22	19	17
AERMOD	-20	110	67	47	41	26	15	11	8	6	6	5	4	3
	-10	110	67	48	42	26	17	12	9	7	6	5	4	3
	0	113	68	48	43	26	17	12	9	7	6	5	4	3
	10	113	69	51	45	26	18	12	9	7	5	5	4	3
	20	118	71	57	49	27	18	13	9	7	5	5	4	3
	30	138	94	60	49	28	19	13	9	7	6	5	4	4

4.3.3 Atmospheric Stability Class

Impact of atmospheric stability class was analyzed under three different wind speeds, i.e., 2, 3 and 5 m/s. With wind speeds of 2 and 3 m/s, stability classes analyzed were D, E and F; with wind speed of 5 m/s, stability classes were C, D and E. The selection of combination of atmospheric stability class and wind speed was based on the relationship between wind speed and atmospheric stability class in Table 4.2. Wind direction of NNW as well as mixing height of 1500 m was chosen. Ambient temperature of 20 ^{o}C was selected.

4.3.3.1 Impact on Critical Odour Detection Distance

Impact of atmospheric stability class on the CDD for these two models is shown as Figure 4.3. The figure shows that odour can travel longer distance under more stable stability classes for both models. For example, when wind speed was 2 m/s, the CDD increased 203 and 100% from stability class D to E for CALPUFF and AERMOD, respectively. Guo et al. (2003) also reported that the majority of odour events were reported during either moderately or slightly stable atmospheric conditions. The discrimination of CDD between two models increased following the change of stability class to next more stable level. Again, when wind speed was 2 m/s, the CDD discrimination was 0.3, 0.5 and 4 km. This trend happened when wind speed were 3 and 5 m/s too. Although influence of stability class at CALPUFF was significant, its influence at AERMOD was not that huge compared with CALPUFF, which can be seen from the change of CDD of AERMOD in Figure 4.3. There may be mainly two reasons: One is AERMOD itself is not sensitive to change of stability class, and the other is AERMOD did not use Pasquill stability class as other models to specify weather conditions so that the discrete Pasquill stability class can not reveal the effects of stability on AERMOD prediction.



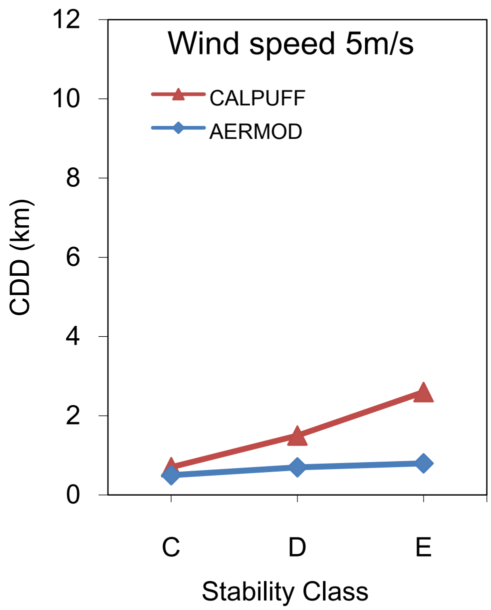


Figure 4.3 Impact of atmospheric stability class on CDD

4.3.3.2 Impact on Odour Concentrations within 5 km

Two models predictions of centerline odour plume concentrations within 5 km are presented in Tables 4.7 to 4.9. For both models, the odour concentration increased following the change of stability class to next more stable level. For example, when stability class changed from D to F under wind speed of 2 m/s, odour concentration increased 51.5 and 126.9% at distance of 0.2 km, 140 and 164% at distance of 1.5 km for CALPUFF and AERMOD, respectively.

Table 4.7 Centerline concentrations of odour plume under wind speed 2 m/s (OU/m^3)

Model	Stability class	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	D	171	139	66	56	36	26	19	15	11	9	8	6	6
	E	175	157	99	82	50	39	32	26	21	18	15	13	11
	F	259	215	163	135	76	60	51	45	39	38	31	27	24
AERMOD	D	160	114	87	77	41	25	17	13	10	8	7	6	5
	E	356	228	173	157	98	65	46	35	27	22	19	16	14
	F	363	232	176	159	100	66	47	35	28	23	19	16	14

Table 4.8 Centerline concentrations of odour plume under wind speed 3 m/s (OU/m^3)

Model	Stability class	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	D	114	93	44	37	24	18	13	10	8	6	5	4	4
	E	120	117	66	55	34	27	21	17	14	12	10	9	8
	F	173	144	109	91	51	40	35	31	27	24	21	19	17
AERMOD	D	97	49	38	32	16	9	7	5	4	3	3	2	2
	E	113	64	52	44	22	13	9	7	5	4	4	3	3
	F	118	71	57	49	25	15	10	8	6	5	4	4	3

Table 4.9 Centerline concentrations of odour plume under wind speed 5 m/s (OU/m^3)

Model	Stability class	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	C	48	39	15	13	7	4	3	2	1	1	1	1	0
	D	74	42	27	23	15	11	8	6	5	4	3	3	2
	E	71	61	40	33	20	16	13	11	9	7	6	5	5
AERMOD	C	54	28	17	16	8	5	3	3	2	2	1	1	1
	D	57	30	19	17	9	6	4	3	2	2	1	1	1
	E	58	31	22	18	11	7	4	3	2	2	1	1	1

4.3.4 Wind Speed

Impact of wind speed on the models' prediction was simulated under atmospheric stability class D and E. When the stability class was D, wind speed was set to 1, 2, 3, 4, 5, 6, 8 and 15 m/s; when the stability class was E, wind speed was set to 2, 3, 4 and 5 m/s. Wind direction of NNW as well as mixing height of 1500 m was chosen. Ambient temperature of 20 ^{o}C was selected.

4.3.4.1 Impact on Critical Odour Detection Distance

As shown in Figure 4.4, when wind speed increased, the CDD decreased sharply under the same stability class. For example, when wind speed increased from 2 to 5 m/s, the CDD decreased by

54 and 76.7% under D, 48 and 86.7% under E for CALPUFF and AERMOD, respectively. Guo et al., (2003) stated that the high turbulence associated with wind speed enhanced air mixing and therefore increased the vertical odour dispersion, causing the odour transportation distance decreasing. The figure also indicates that AERMOD was more sensitive to wind speed compared with CALPUFF. For example, when wind speed increases from 1 to 2 m/s under D, the CDD decreased by 48 and 64.7% for CALPUFF and AERMOD, respectively.

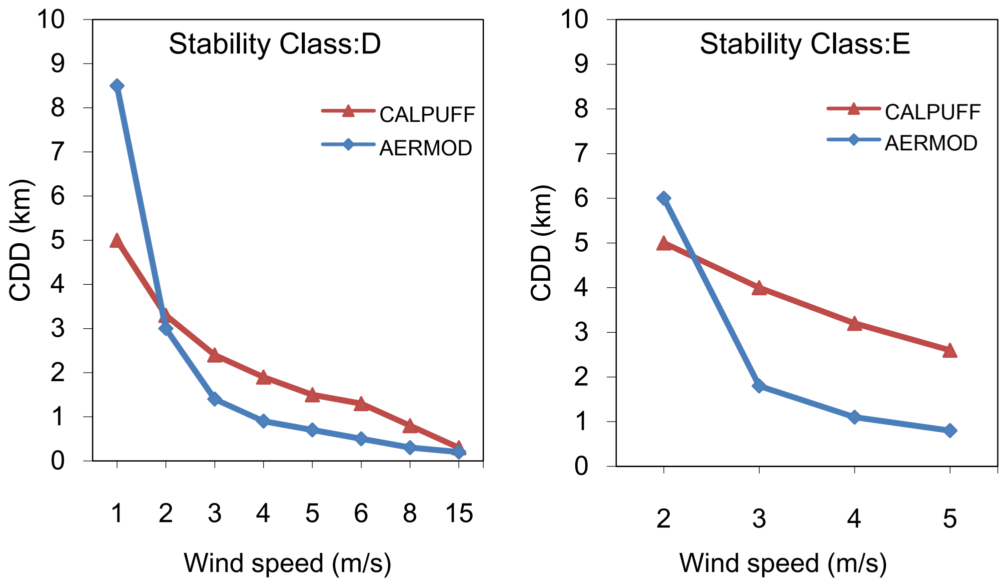


Figure 4.4 Impact of wind speed on CDD under different stability classes

4.3.4.2 Impact on Odour Concentrations within 5 km

As shown in Tables 4.10 to 4.11, the odour concentration decreased with the increase of wind speed at various distances within 5 km under both stability classes D and E. These results agree with the observation of Guo et al. (2003) that high odour concentration occurred when wind speed was low. For example, the odour concentration decreased by 90 and 97.7% when wind speed changed from 1 to 15 m/s under stability class D at distance of 0.2 km, and 59.4 and 83.7% when wind speed changed from 2 to 5 m/s under stability class E at the same distance for

CALPUFF and AERMOD, respectively. It could also be observed that when the wind speed was low, odour concentration are higher as predicted by AERMOD than that of CALPUFF, but lower when wind speed was high.

Table 4.10 Centerline concentrations of odour plume under stability class D (OU/m^3)

Model	Wind speed (m/s)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	1	259	258	130	110	70	51	37	28	22	17	12	12	10
	2	157	171	66	56	36	26	19	15	11	10	8	7	6
	3	114	120	44	37	24	18	13	10	8	6	5	4	4
	4	88	92	33	28	18	13	10	8	6	5	4	3	3
	5	72	74	27	23	15	11	8	6	5	4	3	3	2
	6	60	62	22	19	12	9	7	5	4	3	3	2	2
	8	46	47	17	14	9	7	5	4	3	2	2	1	1
	15	25	25	9	7	5	4	3	2	2	1	1	1	1
AERMOD	1	763	459	322	269	143	93	66	51	40	33	28	24	21
	2	160	114	87	77	41	25	17	13	10	8	7	6	5
	3	97	49	38	32	16	9	7	5	4	3	3	2	2
	4	70	35	24	20	10	6	4	3	2	2	2	1	1
	5	54	28	17	14	7	4	3	2	2	1	1	1	1
	6	43	24	12	10	5	3	2	2	1	1	1	1	1
	8	32	17	9	7	4	2	1	1	1	1	1	0	0
	15	16	9	4	4	2	1	1	0	0	0	0	0	0

Table 4.11 Centerline concentrations of odour plume under stability class E (OU/m^3)

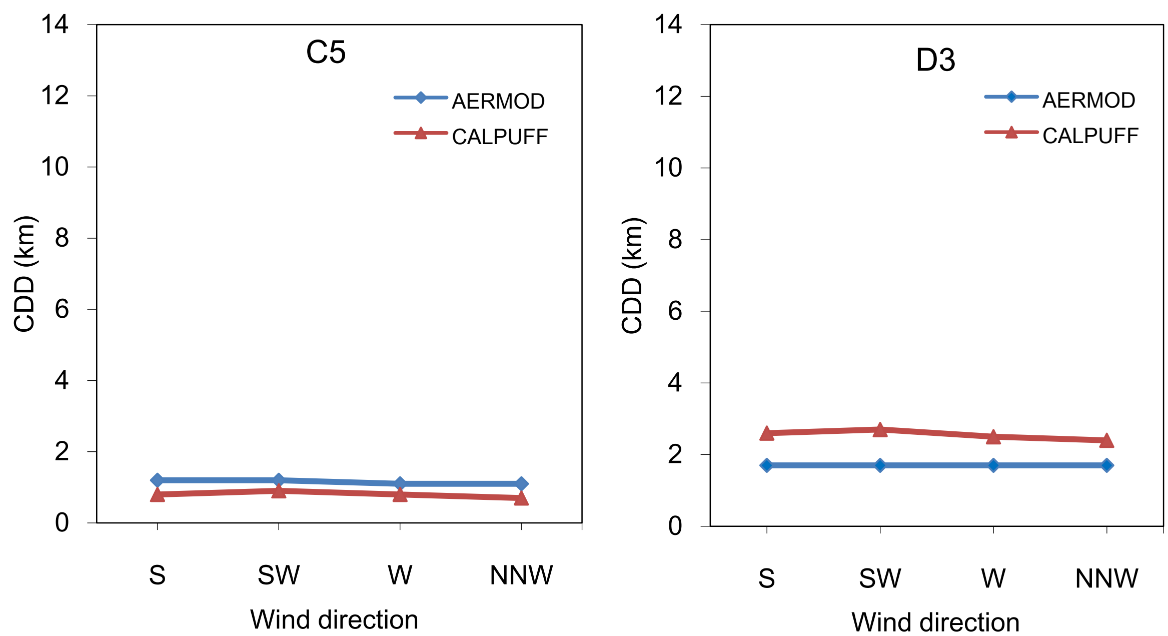
Model	Wind speed (m/s)	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	2	175	139	99	82	50	39	32	26	21	18	15	13	11
	3	117	93	66	55	34	27	21	17	14	12	10	9	8
	4	88	70	50	41	25	20	16	13	11	10	8	7	6
	5	71	61	40	33	20	16	13	11	9	7	6	5	5
AERMOD	2	356	228	173	157	98	65	46	35	27	22	19	16	14
	3	113	64	52	44	22	13	9	7	5	4	4	3	3
	4	78	41	29	24	12	8	5	4	3	2	2	2	2
	5	58	31	19	16	8	5	4	3	2	2	1	1	1

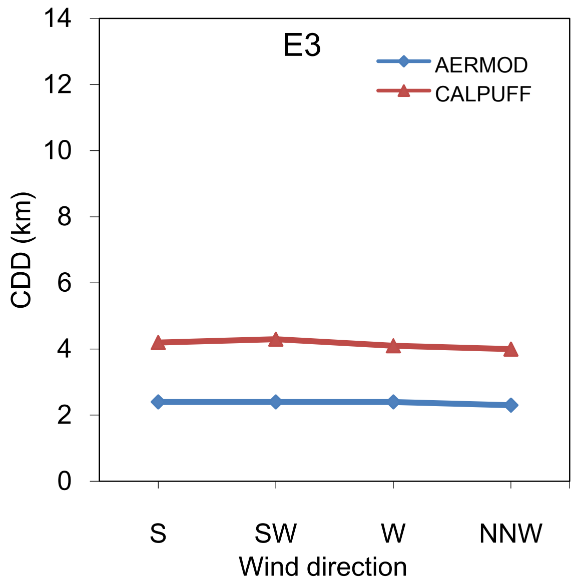
4.3.5 Wind Direction

Wind directions of S (south), SW (southwest), W (west), and NNW (north-northwest) were chosen. Combination of atmospheric stability class as well as wind speed selected was: C3, D5, E3 and F2. Mixing height of 1500 m as well as ambient temperature of 20 ^oC was selected.

4.3.5.1 Impact on Critical Odour Detection Distance

As shown in Figure 4.5, the longest CDD was under the wind direction of SW and shortest under NNW and the CDD was almost the same under other two wind directions for both CALPUFF and AERMOD. The reason may be found in the relative position of odour sources. It can be observed in Figure 4.1, downwind odour emissions from three odour sources overlapped under wind direction of SW; however, odour emissions were almost parallel under wind direction of NNW. It also could be noticed from the figure under unstable weather condition, the CDD predicted by AERMOD was longer than that of CALPUFF; however, the results was the opposite when the weather conditions was stable. For example, the difference of CDD was -0.3 and 1 km, i.e., 25 and 59%, under C5 and D3 if AERMOD predicted CDD was used as the base.





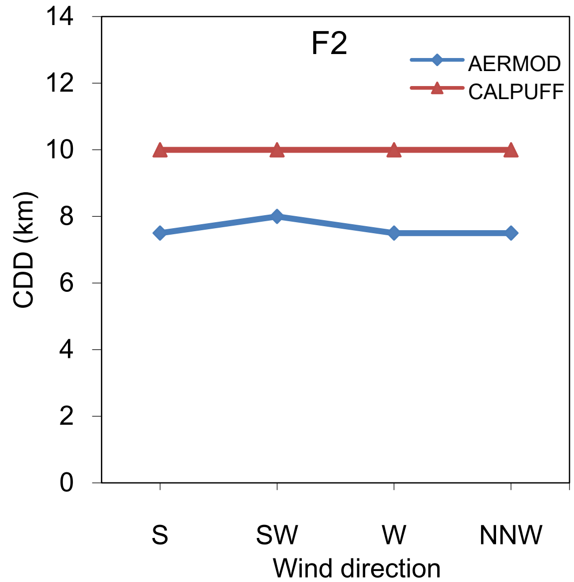


Figure 4.5 Impact of wind direction on CDD under varies weather conditions

4.3.5.2 Effect on Odour Concentrations within 5 km

Tables 4.12 to 4.15 presented the modeled odour concentrations within 5 km from the odour source under C5, D3, E3 and F2. It could be noticed from the figures the influence of changing in wind direction at models predictions were more significant at closer distances to the source than farther distances. At close distance, the differences were distinct; however, these differences diminished following the increase of distance and disappeared at distances near 5 km. This means that wind direction, i.e., building orientation, should be carefully considered when solving odour problem at short distance to odour source. For CALPUFF, the largest discrimination of odour concentration that happened at the closest distance (2 km) under C5, D3, E3 and F2 was 65, 61.2, 48.6 and 20.4% respectively; while for AERMOD, it was 62, 64.2, 56.4 and 33.3%, respectively.

Table 4.12 Centerline concentrations of odour plume at different wind directions under C5 (OU/m^3)

Model	Wind direction	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	S	93	28	23	19	8	4	3	3	2	1	1	1	0
	SW	137	68	43	31	10	5	3	3	2	1	1	1	0
	W	101	41	18	16	8	4	3	3	2	1	1	1	0
	NNW	48	39	15	13	7	4	3	3	2	1	1	1	0
AERMOD	S	73	40	29	22	9	5	4	3	2	2	1	1	0
	SW	150	61	38	27	10	6	4	3	2	2	1	1	1
	W	95	36	22	18	9	5	3	3	2	2	1	1	1
	NNW	57	30	19	16	8	5	3	3	2	2	1	1	1

Table 4.13 Centerline concentrations of odour plume at different wind directions under D3 (OU/m^3)

Model	Wind direction	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	S	245	67	61	55	32	21	14	11	8	7	5	5	4
	SW	294	191	137	106	42	24	16	11	9	7	6	5	4
	W	240	113	49	43	28	19	14	10	8	6	5	4	4
	NNW	114	120	44	37	24	18	13	10	8	6	5	4	4
AERMOD	S	230	74	55	48	27	14	8	6	5	4	3	2	2
	SW	302	70	51	43	27	14	8	6	5	4	3	2	2
	W	235	108	40	32	25	13	8	6	4	4	3	2	2
	NNW	108	96	37	29	23	13	8	6	4	4	3	2	2

Table 4.14 Centerline concentrations of odour plume at different wind directions under E3 (OU/m^3)

Model	Wind direction	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	S	198	85	58	59	46	34	25	20	16	13	11	9	8
	SW	220	145	123	113	66	42	29	22	17	14	11	9	8
	W	117	87	71	60	40	31	24	19	15	13	11	9	8
	NNW	113	93	66	55	34	27	21	17	14	12	10	9	8
AERMOD	S	148	98	73	57	24	14	10	9	6	4	4	3	0
	SW	280	143	93	67	25	15	10	9	6	5	4	3	3
	W	188	78	61	50	23	14	10	9	5	4	4	3	3
	VNW	122	98	50	43	28	16	10	8	4	4	3	2	2

Table 4.15 Centerline concentrations of odour plume at different wind directions under F2 (OU/m^3)

Model	Wind direction	Distance (km)												
		0.2	0.3	0.4	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
CALPUFF	S	273	175	76	87	93	80	67	56	47	40	34	30	26
	SW	314	255	235	221	162	116	86	67	54	44	37	32	28
	W	259	197	163	139	87	70	59	51	43	38	33	29	26
	NNW	250	215	163	135	76	60	51	45	39	35	31	27	24
AERMOD	S	385	238	225	204	114	71	49	37	29	23	19	16	14
	SW	441	416	386	302	184	81	54	45	38	30	22	18	15
	W	309	228	199	180	107	68	48	36	28	23	19	16	14
	NNW	294	222	176	159	100	66	47	35	28	23	19	16	14

4.3.6 Variable Meteorological Conditions

The simulated results of annual average odour concentrations are shown in Figures 4.7 and 4.8. Compared with more smooth contour shape CALPUFF presented, it seems there are some edges on AERMOD simulating contour. The reason is that AERMOD preprocessor AERMET would automatically divide wind directions of 360 degrees into 36 directions, appearing on the contour map the odour traveled longer distance at these directions (USEPA, 2004). According to the statistical results of the weather data of this year the positions of the edges on the contour were these specified wind directions.

These two contours show odour travels longer distance when the wind came from direction of NNW and shorter at wind direction of NE. From the wind rose (Figure 4.6), we can see NNW is the prevailing winds direction and NE is the wind direction with very low occurrence frequency. Schauberger et al. (2005) also concluded that the highest of the direction-dependent separation distances were found for the prevailing wind directions when they conducted sensitivity analysis of Austrian odour dispersion model.

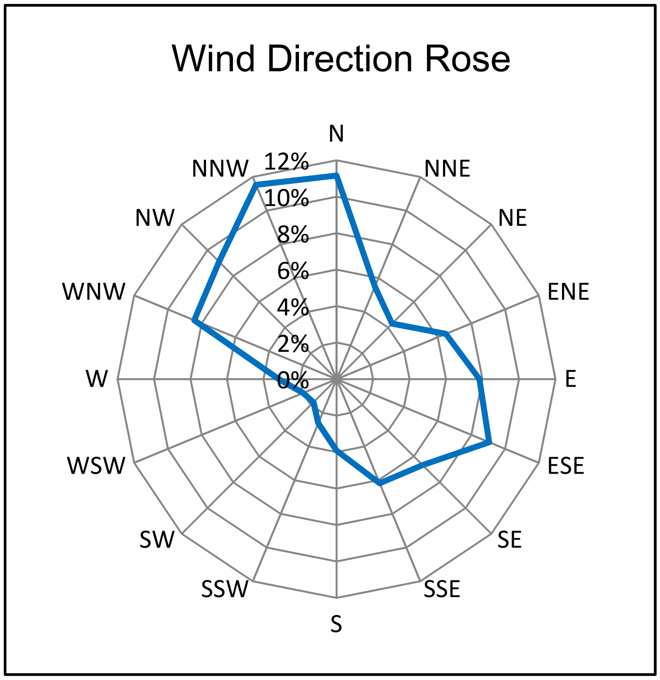


Figure 4.6 Wind direction rose for the simulated area

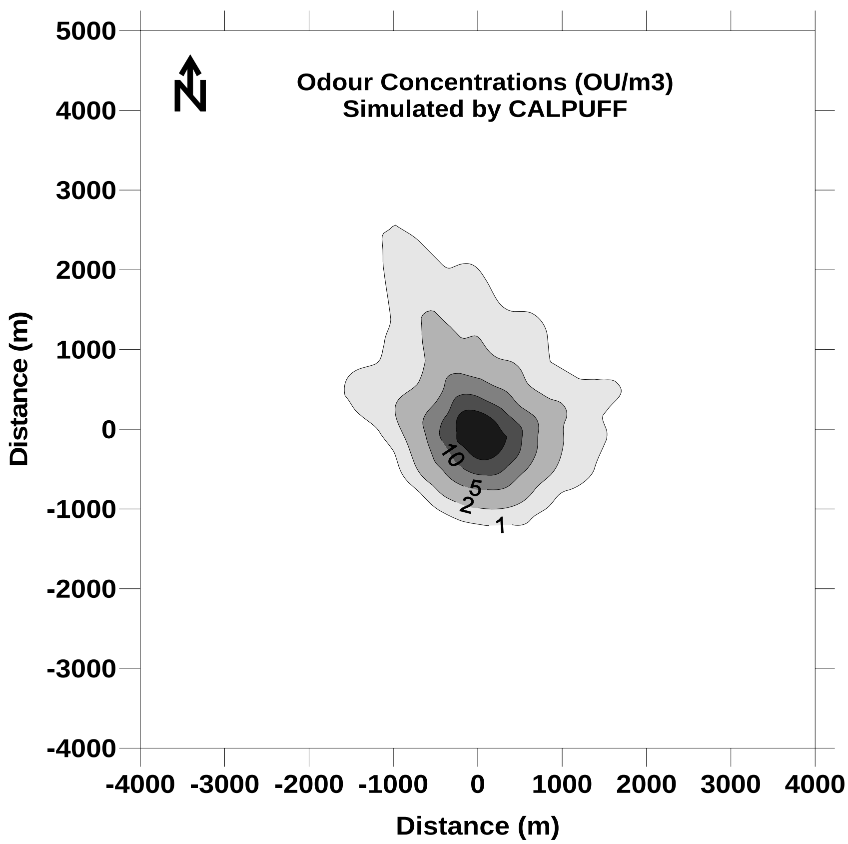


Figure 4.7 Annual average odour concentration contour map simulated by CALPUFF

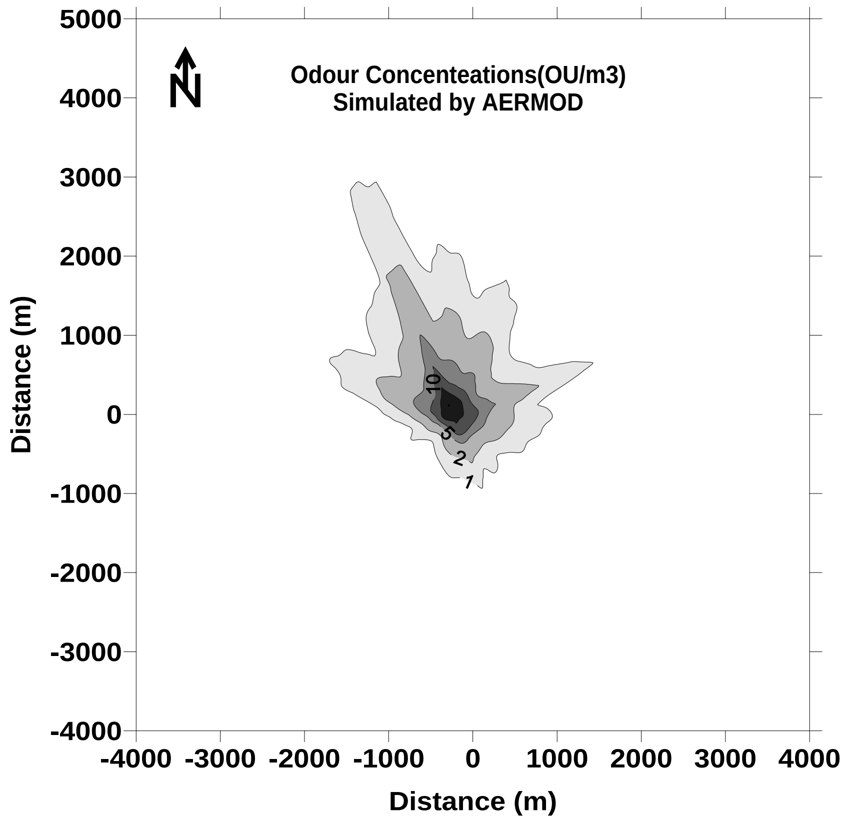


Figure 4.8 Annual average odour concentration contour map simulated by AERMOD

The maximum odour travel distance downwind the farm for odour concentrations of 1, 2, 5 and 10 OU/m^3 is presented in Table 4.16.

Table 4.16 Maximum odour travel distance for different odour concentration level as predicted by CALPUFF and AERMOD

Odour concentration level (OU/m^3)	Maximum odour travel distance (km)	
	CALPUFF	AERMOD
1	3.3	3.5
2	2	1.4
5	1	0.6
10	0.75	0.5

It can be observed from above table model predicted maximum odour travel distance is different for each odour concentration value for two models. CALPUFF over-predicted AERMOD at each odour concentration level except for 1 OU/m^3. CALPUFF predicted distance was 6, 30, 33.3 and 48.9% higher than that of the AERMOD for odour concentration of 2, 5, and 10 OU/m^3, respectively. However, CALPUFF prediction was 6.1% lower than AERMOD for odour concentration of 1 OU/m^3. Schmidt et al. (2006) compared the modeling results of CALUFF and AERMOD and also found that there were some differences between the predicted results of these two models when conducting odour concentration prediction near a 2,000 head finishing site in Minnesota over five years. If the modeling results of these two models are used as the setback distance criteria there will be great difference. Why such huge differences? The reasons may be the different methods these two models adopted to treat the calm weather condition and the theories used to express movement of odour in atmosphere. Scire et al. (2000) indicated that CALPUFF had advantages compared with plume models like AERMOD in handling calm and stagnant weather condition. When it was in calm weather, especially when the wind speed was zero, odour would not travel and the concentration around the odour source would be zero as predicted by AERMOD. According to statistical result of the weather condition of 2003, there were 503 hours with the wind speed of zero, accounting for 5.74% of the whole time. But when the wind speed was relatively small but not zero and the weather was very stable, the odour would travel much longer distance as predicted by AERMOD, which can be seen from steady-state analysis part above. Different theories of treating odour plume were applied by CALPUFF and AERMOD. In CALPUFF, the odour was deemed as puffs. Puffs could be accumulated from time to time as they disperse in air. In AERMOD, however, odour was treated as separated plume. Plume had no memory, i.e., previous plume had no effect on later one. The principle that the accumulated effect of hour by hour odour during the transportation adopted by puff and no effect of previous plume on later one adopted by plume was an important reason for the difference produced by these two models. The difference was also be aggregated by the different method of treating odour plume dispersion during calm weather condition (USEPA, 1998).

As stated previously, the odour travel distance with odour concentration of 10 OU/m^3 predicted under variable meteorological condition was longest at prevailing wind directions as predicted by both AERMOD and CALPUFF. Subsequently, an appropriate odour setback distance should be dependent at wind direction, i.e, setback distance should be longer under prevailing wind directions, and shorter under other directions. Compared with the maximum odour travel distance with odour concentration of 10 OU/m^3 predicted under variable meteorological condition, the critical odour detection distance predicted under steady-state weather conditions was longer under some circumstances, but shorter under other circumstances. For example, the maximum odour travel distance with odour concentration of 10 OU/m^3 predicted under variable meteorological condition was 0.75 and 0.5 km for CALPUFF and AERMOD, respectively; while, the value of CDD was 0.3 and 0.2 km under D15, and 5 and 6 km under F2 under steady-state weather conditions. So if we want to use steady-state weather data to predict odour setback distance, we have to change the meteorological parameters according to the real weather condition of the simulated area. If the actual weather of the case area is moderately stable or even calm at the most time of the year, we have to choose stable stability class and low wind speed; in contrast, if the actual weather there is unstable, we should pick up relatively unstable stability class and high wind speed.

Another thing may be pointed out is that Zwicke (1998) and Fritz et al. (2005) found that using 1 hr time interval for Gaussian-based dispersion models might result in overestimated downwind concentrations compared to a series of controlled pollutant release and experiments. Using 1 hr computational time interval may not accurately characterize an instantaneous odour plume (Li and Guo, 2006). Difference of odour concentration between 1 hr average time and instantaneous should be taken into account when choosing meteorological data. A more appropriate time interval for a specific air dispersion model is needed to best represent the real odour concentration value.

4.4 Conclusions

1. Mixing heights of 100, 200, 500, 1500, 3000 and 5000 m had no impact on agricultural odour dispersion as simulated by both CALPUFF and AERMOD. The reason may be agricultural odour transported very low in air, just a few meters above ground;
2. Although ambient temperature had very limited influence at both of two models, there was a trend with increase of temperature, the odour concentration within 5 km from the odour source increased as predicted two models. The reason may be that when temperature increased, more odour molecules moved into the odour transportation direction, causing higher odour concentration in horizontal direction;
3. Atmospheric stability class had great impact on CDD as predicted by both models. As the weather condition changed from D to F, the CDD increased 203 and 100% at wind speed 2 m/s, 213 and 43% at wind speed 3 m/s for CALPUFF and AERMOD, respectively. Odour concentration values within 5 km increased following the change of stability class to next more stable one at the same distance under the same wind speed. The reason of this is that when the atmosphere is stable, odour can travel longer distance without disturbed by the mixing of the vertical and horizontal air. The simulated results also showed that CALPUFF was more sensitive to the stability class change compared with AERMOD;
4. Under the same atmospheric stability class, the CDD decreased greatly as the wind speed increased for both models. When wind speed increased from 2 to 5 m/s, the CDD decrement was 54.5 and 76.7% under stability class D, and 48 and 86.7% under E for CALPUFF and AERMOD, respectively. Odour concentrations within 5 km decreased following the increases of wind speed at the same distance under the same atmospheric stability class. It

also indicated that AERMOD was more sensitive to wind speed change compared with CALPUFF;

5. The analysis results of impact of wind direction on CDD and odour concentrations within 5 km showed that wind direction had effect on the odour concentration because of the source orientation against the wind direction. This effect was distinct at close distance to the odour source and diminished and even disappeared at long distance of 5 km. Based on the fact that each animal production site consists of barns and manure storage cells, wind direction should be carefully considered when the farm was close to residential area;
6. The difference of method of treating wind direction caused the difference of the contour shape, i.e., CALPUFF's contour lines were smooth while AERMOD's had sharp edges. The reason was CALPUFF treated wind direction as 360 directions while AERMOD only divided 360 degrees into 36 directions;
7. Variable annual hourly meteorological data simulation result showed CALPUFF predicted longer maximum odour travel distance than AERMOD for selected odour concentration values of 2, 5, 10 and 20 OU/m^3 but lower for 1 OU/m^3. The difference was 6, 30, 33.3, 48.9 and 6.1% for odour concentration of 2, 5, 10, 20 and 1 OU/m^3, respectively. Different methods used to deal with calm weather condition and theories used to describe movement of odour plume in atmosphere may be two reasons caused the discrimination of models predictions;
8. To predict appropriate odour setback distance for an odour source, the setbacks should be wind direction dependent, i.e., setback distance should be longer under prevailing wind directions and shorter under other directions. Both steady-state and variable meteorological data could be employed to predict odour setback distance; however, proper values should be given to the climatic parameters if steady-state meteorological data are used or say acceptable odour concentration should be based on the climatic parameters chosen under steady-state weather conditions.

5. EVALUATION OF AERMOD AND CALPUFF FOR ODOUR DISPERSION USING FIELD MEASURED ODOUR DATA: PART I. USING ODOUR PLUME MEASUREMENT DATA FROM UNIVERSITY OF MINNESOTA

5.1 Introduction

Evaluation and comparison of air dispersion models not only give us an opportunity to understand the capability of models simulating odour dispersion but also provide an access to know which model is the best to predict odour concentration for a general case of odour source. Evaluation of model required model predictions and field odour measurements.

Model was prepared using odour emissions, meteorological data, and parameters describing the terrain condition, and setting of odour receptors and then was run to produce odour concentrations in the vicinity of the odour source. However, field odour measurements were performed through letting human sniffers standing in the field downwind the odour source to sniff the odour they detected. The odour these human sniffers detected was recorded as the field measurement. The model predictions were then could be compared with the field measurements. During this process of comparison, some mathematical methods (e.g., scaling factor) can be applied to improve the agreement of field measured and predicted values. Evaluation of models requires a large amount of field odour data, which could be only available recently based on a lot of work done by researchers and trained odour sniffers or resident-odour-observers.

This part of the project aims at evaluating the performance of two air dispersion models, CALPUFF and AERMOD, through comparing the models predictions with field measurements using the field odour data from University of Minnesota. Comparison of models predictions between these two models was also made to find out which model is better. Another purpose of this part is to recheck the scaling factors yielded in this project to see if they are the same as those obtained in Zhu, (2000).

5.2 Materials and Methods

Evaluation of models required odour emissions of the odour source(s), field odour data, meteorological data, and terrain condition surrounding the odour source(s). Odour emissions from the odour source(s), field odour data, and meteorological data were obtained by a research group charged by Dr. L. D. Jacobson, a faculty member of University of Minnesota in 1998. Meteorological data were also recorded by odour sniffers involved in that project.

5.2.1 Site Description and Odour Emission Rates

A Farmland with location of 94.19W (Longitude) 44.28N (Latitude) at an elevation of 302 m above MSL near Nicollet county in south central Minnesota was chosen to monitor odour occurrence. This area was surrounded by agricultural land and was relatively flat, so the influence of topography on the odour dispersion was minimal. A total of 28 farm sites were visited, which covered most of the animal species (Zhu et al., 1999). We conducted odour prediction simulation on eight farm sites in this project because the field measurement data of odour occurrence and weather condition data were only available from these farms. Air samples for determining odour emission rates from each odour source on the farm sites were collected at the same time as odour plume measurement. For some farms, only odour emissions from barn were measured, while for others only EMS emissions were measured, and for some farms both barn and EMS emissions were measured. The details of emission rates are presented in Table 5.1.

Table 5.1 Odour Emission rates of selected farms in Minnesota (Jacobson et al., 1998)

Farm ID	Source type	Measured time	Total odour emissions (OU)	Odour emission rate (OU/s-m^2)
203	EMS	Am - 06/03/98	320134	41.30
		Pm - 06/03/98	207118	26.70
217	EMS	Am - 04/29/98	8106	4.45
		Pm - 04/29/98	14102	7.73
219	Barn	Am/Pm - 04/22/98	998	1.72
220	EMS	Am - 06/16/98	27747	6.53
221	Barn	Am - 04/22/98	298	1.67
		Pm - 04/22/98	2125	11.85
222	Barn	Am - 06/10/98	1327	1.73
223	Barn	Am - 05/20/98	4727	2.48
		Pm - 05/20/98	5672	2.97
224	Barn	Am - 06/10/98	5286	6.89
		Pm - 06/10/98	5343	6.97

5.2.2 Field Odour Plume Measurement

As described in Jacobson et al. (1998), seven trained human sniffers were taken to the field to carry out on-site odour intensity measurements. Distances between 25 to 500 m were marked off along approximately the centerline of the odour plume depending upon farm site and strength of odour from the source. Straight lines were drawn perpendicular to this centerline to locate each individual sniffer 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 involved plume width. Intensity scales of 0 - 5 (0: no odour; 1: very faint; 2: faint; 3: distinctly noticeable; 4: strong; 5:

very strong odour) with constant interval of 0.5 was used by human sniffers to assess the odour intensities detected. Human sniffer scores were taken every 10 seconds (6 seconds for sniffing and 4 seconds for resting) in a period of 10 min session, i.e., there were 60 records in each session for each sniffer. A total of 30 sessions of data were taken over eight different farms in six days in 1998. For each day, two or three sessions of data were taken in the morning and/or afternoon at different short range of distances (25 to 300 meters) downwind odour source. The averaged values recorded in each single session for every sniffer were deemed as the odour intensity that sniffer got in that odour plume testing action. The detailed procedure to measure the odour plume was presented at Jacobson et al. (1998).

At each farm site, a portable weather station about two meters high was employed to collect on-site weather data including wind speed and direction, solar radiation, temperature, and relative humidity. The weather data were recorded at the same time the odour plume intensities were recorded. These weather data were then used in the model to calculate the downwind odour concentration for that specific site. Field weather data (e.g., temperature, wind speed) recorded by the weather station in each 10 min session were averaged and were deemed as the weather data in that session. Every averaged weather data in that session were prepared for the input of air dispersion models and were considered to be the same as the hourly meteorological data that the models usually need.

5.2.3 Model Configuration

AERMOD of version 02222 and CALPUFF of version 5.7 were used in this part. Most of the configurations of two models were the same as those addressed in chapter 4.2.4 of models configuration; however, some there were still some differences should be specified based on simulation situation in this part. The differences were:

a) Simulation time was changed to correspond the time field odour data were taken;

b) Odour emission rates were prepared according to Table 5.1;

c) The elevation of the simulated area was 302 m;

d) Field measured meteorological data in this part were used here;

e) The type of odour receptors was discrete receptors, and the location of these receptors were specified according to the location of human sniffers involved in this part that stood in the field to sniff and record the odour intensity;

f) For the upper air data used in AERMOD, The location of the nearest upper air station was 93.55W (Longitude), 44.83N (Latitude);

g) For both AERMOD and CALPUFF, value of surface roughness length was set to 0.03 in April, 0.20 from May to June according to Table 4.5. For AERMOD, value of Albedo and Bowen ratio was set to 0.14 and 0.3 in April, 0.20 and 0.5 from May to June according to Table 4.5.

5.2.4 Relationship between Odour Concentration and Intensity

Concentration-intensity conversion equation from University of Minnesota derived from Minnesota field measured odour data used 5-pint (0 - 5) scales, however, Concentration-intensity conversion equation from University of Alberta derived from Alberta field measured odour data used 8-point (0 - 8) scales. In order to find out which conversion equation is more accurate to express relationship between concentration and intensity, both conversion equations from University of Minnesota and University of Alberta , i.e., equations 2.1, and 2.3, were used in this part to convert modeled concentrations to corresponding intensities to be compared with field measured intensities.

5.2.5 Comparison between Model Predicted and Field Measured Odour Intensity

A pair of data was defined as one model predicted odour intensity and the corresponding field measured odour intensity. A total of 196 pairs of data (including field measured intensity 0) were compared between the model predictions and field measurements for both models, respectively. As stated previously, because the odour sniffers applied 5-point scales to recorded odours they detected, and the final result was the average of all records in each 10-min session, the measured values could be any values in the range of 0 - 5. Subsequently, each measured intensity value covers ±0.5 range, e.g., if the measured value is 3, then it covers 2.5 to 3.5. Hence, if the predicted odour intensity is within ±0.5 of the measured intensity, the predicted value is considered to be in agreement with the corresponding measured one. For example, if the measured intensity is 2 and the predicted intensity falls into the range of 1.5 to 2.5, the predicted value and corresponding measured one are considered in agreement, otherwise, we deem them disagreeing.

Sometimes, the odour sniffers did not detect any odour, i.e., the detected odour intensity was 0. In order to find out the impact of field measured odour intensity 0 on the agreement of modeled and field measured odour occurrences, comparison of model predicted and field measured odour intensity was conducted under two situations as a) comparison was made using all field measured odour intensities, including intensity 0; b) comparison was made using field measured odour intensities, excluding intensity 0. Under the situation b, measured intensity 0 were kicked out, leaving the rest values to be averaged to compare with corresponding modeled ones. If all measured odour intensities were 0 by any sniffer in any odour data measurement session, we would ignore the field measured odour by that sniffer in that session. According to the statistical results of Minnesota field measured odour intensities, there were three sessions in which all measured odour intensities were 0, i.e., only 193 pairs of data could be compared if excluding field measured intensity 0.

5.2.6 Using an ASTM-Standard Guide for Statistical Evaluation of AERMOD and CALPUFF Performance

The performance of atmospheric dispersion models can be evaluated via a standard guide released by the American Society for Testing and Materials (ASTM) from a statistical point of view (ASTM, 1988). This ASTM Guide is used for assessing the performance of atmospheric transport and diffusion models for predicting the concentration of a pollution plume released from the source (USEPA, 2003). Experience with air quality modeling showed that deviations between model predictions and observations were sometime pretty large. For example, comparisons between 12 regulatory air dispersion models used in some European countries revealed that quite huge differences existed between modeled and measured results (Cosemans et al., 1995). A lot of studies have been done to evaluate models performance in pollution dispersion simulation (Weil, 1992; Olesen, 1998, Olesen, 1999, etc). Evaluation of models performance can be determined by seven statistical parameters, i.e., Bias, the normalized mean square error, the coefficient of correlation, fraction of predictions with a factor of two of observations, the Fractional Bias (FB), the geometric mean variance, and the geometric mean bias (USEPA, 1992). Generally, FB could be used to give an overall estimation of how well the model's predicted results match the corresponding observations (Olesen, 1999). The expression of the Fractional Bias is (ASTM, 1998):

$$FB = \frac{2\,(PR - OB)}{PR + OB} \tag{5.1}$$

Where: *OB* and *PR* refer to the average of the observed (OB) and predicted (PR) values respectively. The same expression is used to calculate the *FB* of the standard deviation, where *OB* and *PR* refer to the standard deviation of the observed and predicted values, respectively.

The FB was selected as a measure of model's performance based on its two desirable features (USEPA, 1992). First, FB is symmetrical and bounded varying between -2.0 (extreme under-prediction) and + 2.0 (extreme over-prediction) and 0 for an ideal model. Second, FB is a dimensionless number, which can show advantages in comparing the results that involve different concentration levels. Value of the FB of -0.67 is equivalent to model under-prediction by a factor of two, while +0.67 is equivalent to over-prediction by a factor of two. The value of FB of a perfect model prediction is 0, meaning free from bias. A low variance in FB can be taken as indicating confidence in the model prediction (McHugh et al., 1999). The FB of average intensity and intensity standard deviation between predicted and measured intensities were calculated to evaluate the models' performance.

5.3 Results and Discussions

Evaluation of AERMOD and CALPUFF through comparing model predicted and field measured odour intensities to find out the agreement between them was presented in this part. Models predicted concentrations were converted to intensities using concentration-intensity conversion equations from University of Minnesota and University of Alberta. Scaling factors were also used to improve the agreement. Discussions of the simulated results as well as statistical evaluation of two models performance using an ASTM-Standard Guide were also made.

5.3.1 Evaluating Models Using Concentration-intensity Conversion Equation from University of Minnesota

Models predictions of odour concentration can be very low at sometimes. We got negative values of intensities when odour concentrations were converted to intensities using conversion equation if this happened. Therefore, the converted values of intensities from model predicted concentrations were set to zero whenever encountered this situation because the concentrations were so low that there could be considered no odour, i.e., both odour concentration and the corresponding intensity were zero. Figures 5.1 and 5.2 show the detailed information of model predicted versus measured odour intensities using conversion equation from University of Minnesota. One example of how modeled intensity versus measured intensity was given here. If the odour concentration predicted by an odour receptor is 30 OU/m^3, using the concentration-intensity conversion equation from University of Minnesota, i.e., equation 2.1 (the farms involved in this part were swine farms), the predicted intensity corresponding to this concentration should be 1.2. If the odour intensity observed by a human sniffer standing at the same location as this odour receptor is 1.5, and then they are marked as a pair of data, presenting a dot in the figures of model predicted versus measured odour intensity. The X and Y-coordinate of the dot that corresponding to this pair of data is (1.2, 1.5). A total of 196 dots were presented in the Figures 5.1 and 5.2.

The straight line of X = Y in the figure was drawn to see how many dots were on it. Those dots converging on X = Y means modeled and measured intensities were the same.

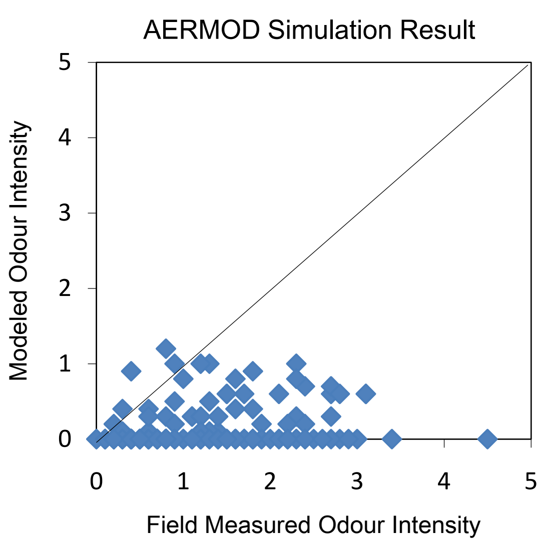


Figure 5.1 AERMOD predicted and field measured odour intensities using conversion equation from University of Minnesota for Minnesota plume data

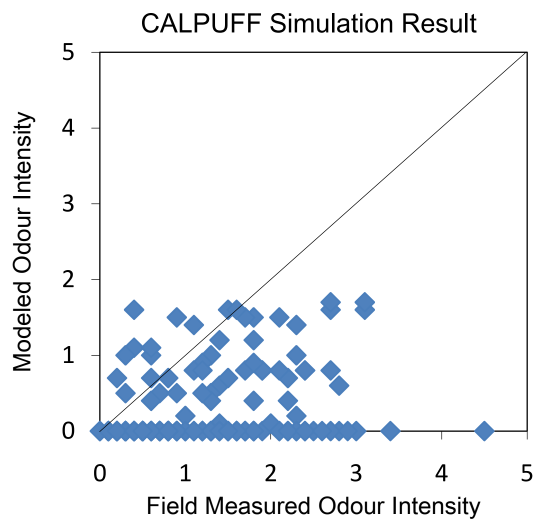


Figure 5.2 CALPUFF predicted and field measured odour intensities using conversion equation from University of Minnesota for Minnesota plume data

Table 5.2 summarizes the agreement of model predicted and field measured odour intensities as well as the number of paired data at distance of 100, 200 and 300 m using conversion equation from University of Minnesota for Minnesota odor data.

Table 5.2 Agreement between model predicted and field measured odour intensities using conversion equation from University of Minnesota for Minnesota plume data

Model	Distance (m)	Total No. of paired data	Agreement No. of paired data	Agreement Percentage (%)
AERMOD	100	154	52	33.8
	200	28	10	35.7
	300	14	6	42.9
	Overall	196	68	34.7
CALPUFF	100	154	53	34.4
	200	28	15	53.6
	300	14	7	50.0
	Overall	196	75	38.3

From Figures 5.1 and 5.2 we can obviously notice most of the dots are under the straight line X = Y, indicating most of the modeled odour intensities are lower than the corresponding field measured intensities. It could also be observed a large portion of dots converge at zero level of the modeled intensity, showing the models predicted concentrations were pretty low though the measured intensities fell into the range of 0 to 5. From Table 5.2 we can see for all selected distances (100, 200 and 300 m) downwind, CALPUFF achieved better agreements compared with AERMOD although the differences are not huge. The difference is 0.6, 17.9 and 7.1% at distance of 100, 200 and 300 m, respectively. For the overall level, CALPUFF again did a better job than AERMOD; the agreement is 34.7 and 38.3% for AERMOD and CALPUFF, respectively. Table 5.2 also shows agreement of modeled and measured odour intensities for both models are poor. Overall level of agreement percentages for both models not even exceeds 40%.

However, if we only consider the measurements with odours detected, i.e., excluding all the odour measurements with intensity zero, the agreement of the modeled and measured intensities was then given in Table 5.3. Figures 5.3 and 5.4 show the detailed information of predicted versus field measured intensities if measured intensity 0 was excluded and conversion equation from University of Minnesota was used for Minnesota odour data.

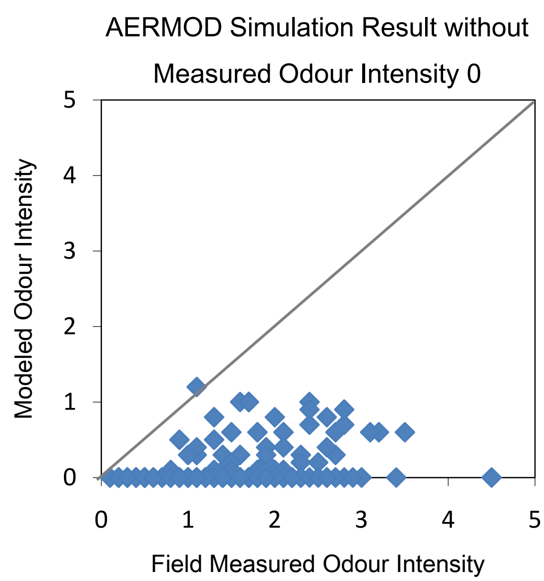


Figure 5.3 AERMOD predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota for Minnesota plume data

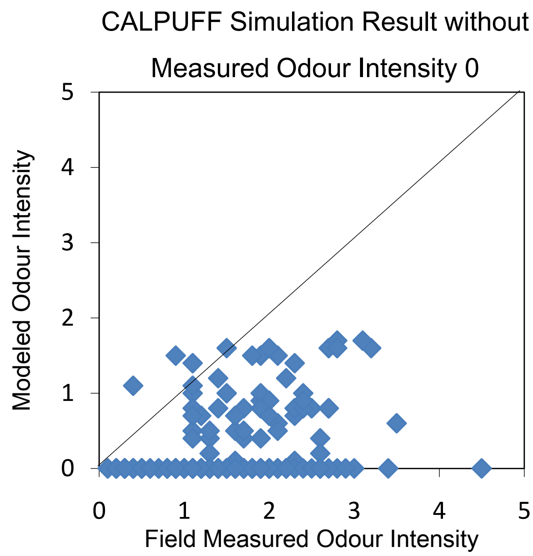


Figure 5.4 CALPUFF predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota for Minnesota plume data

Table 5.3 Agreement between model predicted and field measured odour intensities (excluding measured odour intensity 0) using conversion equation from University of Minnesota for Minnesota plume data

Model	Distance (m)	Total No. of paired data	Agreement No. of paired data	Agreement Percentage (%)
AERMOD	100	151	26	17.2
	200	28	8	28.6
	300	14	0	0
	Overall	193	34	17.6
CALPUFF	100	151	28	18.5
	200	28	11	39.3
	300	14	1	7.1
	Overall	193	40	20.7

From Table 5.3 it could be observed the overall agreement of modeled and measured odour intensities (excluding measured odour intensity 0) was 17.6 and 20.7% for AERMOD and CALPUFF, respectively. Comparing Table 5.2 and 5.3, we can see if intensity zero was not considered, the overall agreement decreased sharply, indicating intensity zero contributed a lot to improve the agreement as shown in Table 5.2. The reasons for low agreement as shown in Table

5.2 and 5.3 include uncertainty in odour intensity measurements by human sniffers, b) the odour emission measurements, c) the uncertainty of using the average of the 10-min session odour plume and weather data measurement, and d) the uncertainty in odour concentration and intensity Minnesota conversion equation.

5.3.2 Evaluating Models Using Concentration-intensity Conversion Equation from University of Alberta

Figures 5.5 and 5.6 show the detailed information of predicted versus measured intensities using conversion equation from University of Alberta for Minnesota odour data. From Figures 5.5 and 5.6 we can observe that dots scatter widely at two sides of the straight line X = Y, indicating either modeled intensities were lower than the corresponding measured ones or the measured intensities were lower than the corresponding modeled ones.

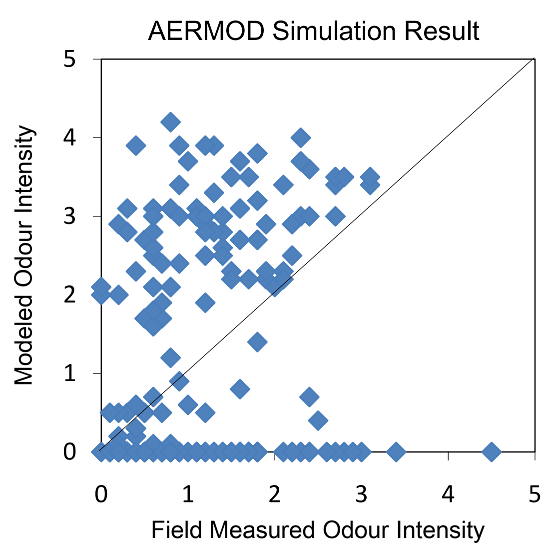


Figure 5.5 AERMOD predicted and field measured odour intensities using conversion equation from University of Alberta for Minnesota plume data

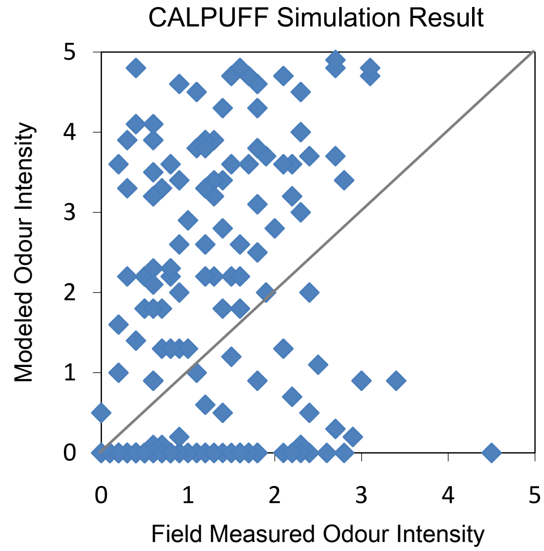


Figure 5.6 CALPUFF predicted and field measured odour intensities using conversion equation from University of Alberta for Minnesota plume data

Table 5.4 shows the predicted and measured odour intensity agreement analysis results using conversion equation from University of Alberta for Minnesota plume data.

Table 5.4 Agreement between model predicted and field measured odour intensity using conversion equation from University of Alberta for Minnesota plume data

Model	Distance (m)	Total No. of paired data	Agreement No. of paired data	Agreement Percentage (%)
AERMOD	100	154	55	35.7
	200	28	11	39.3
	300	14	1	7.1
	Overall	196	67	34.2
CALPUFF	100	154	52	33.8
	200	28	8	28.6
	300	14	1	7.1
	Overall	196	61	31.1

From Table 5.4 we can see for selected distances 100 and 200 m downwind, AERMOD got better agreements compared with CALPUFF although the differences are pretty small. The difference is 1.9 and 10.7% at distance of 100 and 200 m, respectively. They got the same agreement at distance of 300 m. For the overall level, the agreement is 34.2 and 31.1% for

AERMOD and CALPUFF, respectively. The same situation as that in Table 5.2 can be noticed, i.e., agreement percentages of modeled and measured odour intensities for both models are pretty poor. Overall level of agreement percentages for both models is around 33%.

Comparing the outcomes in Tables 5.2 and 5.4, we may find the model performance was partly determined by the conversion equation. When conversion equation from University of Minnesota was used, CALPUFF achieved a better agreement than AERMOD; however, AERMOD got a better agreement than CALPUFF when using conversion equation from University of Alberta was employed. Generally, conversion equation from University of Minnesota is more suitable for both models if Minnesota plume data was used only considering the overall agreement level. Detailed agreement analysis of measured and predicted odour intensities for each intensity level from 0 to 5 are shown in Tables C.1, C.2, C.5 and C.6 in Appendix C. Both of Tables C.1 and Table C.2 present nearly for each intensity level, the measured odour intensity were higher than the corresponding modeled ones; however, Tables C.5 and C.6 present measured intensities were higher than the corresponding modeled ones at some intensity levels and lower at other intensity levels.

Again, if we only consider the measurements with odours detected, i.e., excluding all the odour measurements with intensity zero, then the agreement of the modeled and measured intensities was given in Table 5.5. Figures 5.7 and 5.8 show the detailed information of predicted versus measured intensities using conversion equation from University of Alberta for Minnesota plume data if field measured odour intensity 0 was excluded.

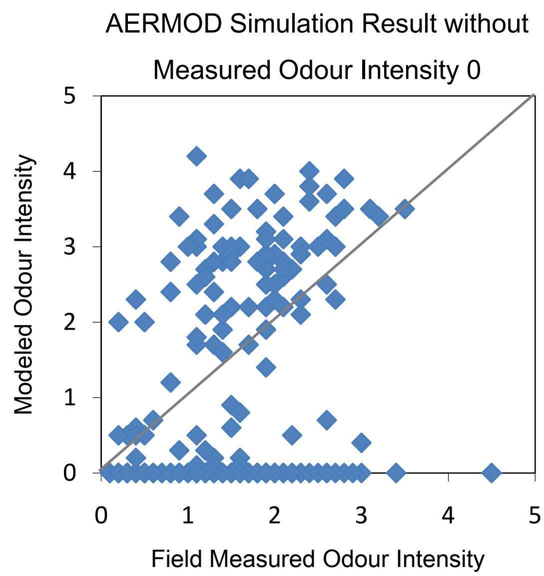


Figure 5.7 AERMOD predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Alberta for Minnesota plume data

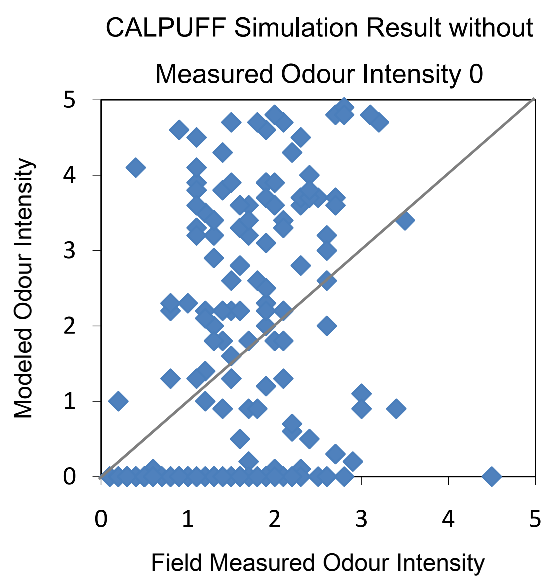


Figure 5.8 CALPUFF predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Alberta for Minnesota plume data

Table 5.5 Agreement between model predicted and field measured odour intensities (excluding measured odour intensity 0) using conversion equation from University of Alberta for Minnesota plume data

Model	Distance (m)	Total No. of paired data	Agreement No. of paired data	Agreement Percentage (%)
AERMOD	100	151	38	25.2
	200	28	11	39.3
	300	14	4	28.6
	Overall	193	53	27.5
CALPUFF	100	151	40	26.5
	200	28	6	21.4
	300	14	4	28.6
	Overall	193	50	25.9

From Table 5.5 it could be observed the overall agreement of modeled and measured odour intensities was 27.5 and 25.9% for AERMOD and CALPUFF, respectively. Comparing Table 5.4 and 5.5, we can see if intensity zero was not considered, the overall agreement decreased greatly, indicating intensity zero contributed some to improve the agreement as shown in Table 5.4.

5.3.3 Adjusting Modeled Results Using Scaling Factors

When using INPUFF-2 model to conduct agricultural odour dispersion simulation, Zhu et al. (1999) found that the odour source emission rates need to be multiplied by a 'scaling factor'(SF) before use as a model input to obtain results that fell into the same numerical magnitude as the field measured data. Applying air dispersion models, which were originally designed for industrial gas pollution as stated before, to predict agricultural odours dispersion sometime got huge differences between the predicted results and field measured ones because odours are so different from industrial gases. Therefore, the approach of using 'scaling factors' to adjust the model input for odour could be considered an attempt in employing air dispersion models for odour dispersion (Zhu et al., 1999). Koppplu et al. (2004) reported that scaling factors in the range of 0.2 to 3900 may be needed to adjust AERMOD predictions to short-term odour measurements depending on the source type (point, area, volume) and the type of facility being modeled after comparing measured odour intensities from livestock facilities to predicted ambient odour levels from AERMOD. A common practice is to get the modeled odour concentration at the receptors' locations for both buildings and manures storages separately and then apply the scaling factors to all odour producing sources and adjust the values of scaling factors to get the desirable ones by comparing the final adjusted total concentrations with the observed ones. The final adjusted total concentrations was expressed by Xing, (2006)

$$C = a \times C_1 + b \times C_2 \tag{5.1}$$

Where:

C: Adjusted total odour concentration;

C_1: Modeled odour concentration from building source;

C_2: Modeled odour concentration from manure storage source, and

a, b: Constants, i.e., scaling factors for barn and manure storage, respectively.

According to Zhu et al. (2000), Barns and manure storages have different scaling factors (35 for the barn and 10 for the manure storage) due to different source characteristics. In order to get most suitable values of a and b, we can start with a = 1 and b = 1 and then increase or decrease the value of b at a constant step of 0.1 while keeping a unchanged, after we finish changing b we turn around to do the same work to a as b and keeping b constant. After these two rounds, we can find out the maximum agreement of adjusted modeled concentrations with observed ones via comparing them. During this process, statistical method could be used to get the most appropriate value for a and b.

Scaling factors for both AERMOD and CALPUFF are listed in Table 5.6 if conversion equation from University of Minnesota was applied for Minnesota plume data.

Table 5.6 Scaling factors using conversion equation of University of Minnesota for Minnesota plume data

Model	Scaling factor	
	Barn	Manure storage
AERMOD	32.5	6.5
CALPUFF	22	4

Figures 5.9 and 5.10 show the detailed information of predicted versus measured odour intensities.

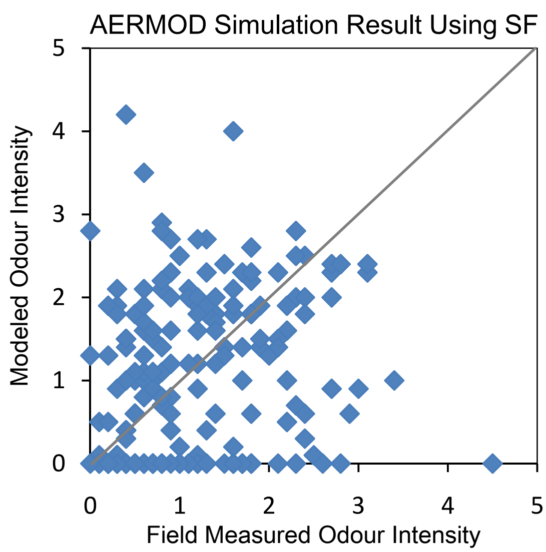


Figure 5.9 AERMOD predicted and field measured odour intensities using conversion equation from University of Minnesota with scaling factors for Minnesota odour plume data

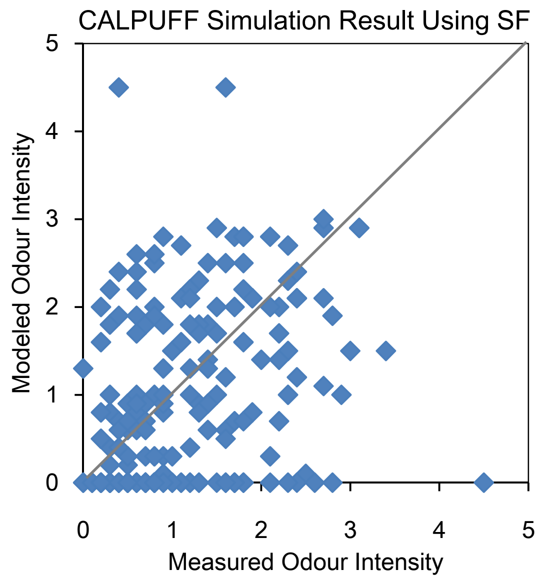


Figure 5.10 CALPUFF predicted and field measured odour intensities using conversion equation from University of Minnesota with scaling factors for Minnesota odour plume data

Table 5.7 shows the original (without scaling factors) and adjusted agreement (after applying scaling factors using conversion equation from University of Minnesota for Minnesota plume data

Table 5.7 Original and adjusted agreement using conversion equation from University of Minnesota for Minnesota odour plume data

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	100	33.8	48.1
	200	35.7	57.1
	300	42.9	50.0
	Overall	34.7	49.5
CALPUFF	100	34.4	49.4
	200	53.6	42.9
	300	50.0	57.1
	Overall	38.3	49.0

Comparing Figures 5.9 and 5.10 with corresponding Figures 5.1 and 5.2, we may find dots converge some to the straight line X = Y in two latter figures. This phenomenon indicates scaling factors can help improve agreement percentage of modeled and measured odour intensities using conversion equation from University of Minnesota.

For AERMOD, the agreement at every distance level got improvement after applying scaling factors. The improvement was 14.3, 21.4 and 7.1% at distances of 100, 200 and 300 m, respectively, and 14.8% for overall level. While for CALPUFF, the improvement was 15 and 7.1% at distances of 100 and 300 m, respectively. Though the agreement went down by 10.7% at distance of 200 m, improvement was 10.7% for the overall level. Based on this result, we may say conversion equation from University of Minnesota with scaling factors was useful for improving agreement of measured and predicted odour intensities for both CALPUFF and AERMOD if using odour plume data measured by University of Minnesota. This conclusion can be consolidated by comparing Tables C.3 and C.4 with Tables C.1 and C.2 in Appendix C. Comparison of Table C.3 with C.1 and C.4 with C.2 turns out the overall agreement percentages increased after using scaling factors, i.e., sum of numbers in blue background unit table increased in Tables C.3 and C.4.

Scaling factors for both AERMOD and CALPUFF are listed in Table 5.8 if field measured odour intensity 0 was excluded and conversion equation from University of Minnesota was applied for Minnesota plume data.

Table 5.8 Scaling factors using conversion equation from University of Minnesota for Minnesota plume data (excluding intensity 0)

Model	Scaling factor	
	Barn	Manure storage
AERMOD	33.6	8.5
CALPUFF	24	7.2

Figures 5.11 and 5.12 show the detailed information of predicted versus measured odour intensities if field measured odour intensity 0 was excluded and scaling factors were used at the same time. Table 5.9 shows the original (without scaling factors) and adjusted agreement (after

applying scaling factors using conversion equation from University of Minnesota for Minnesota odour data.

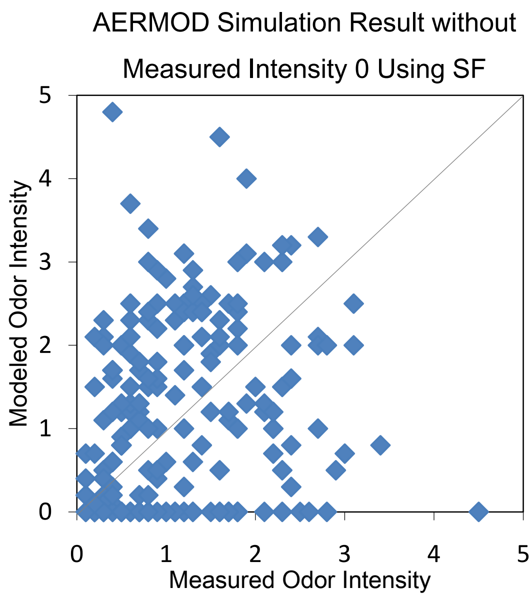


Figure 5.11 AERMOD predicted and field measured odour intensities (excluding odour intensity 0) using conversion equation from University of Minnesota with scaling factors for Minnesota odour plume data

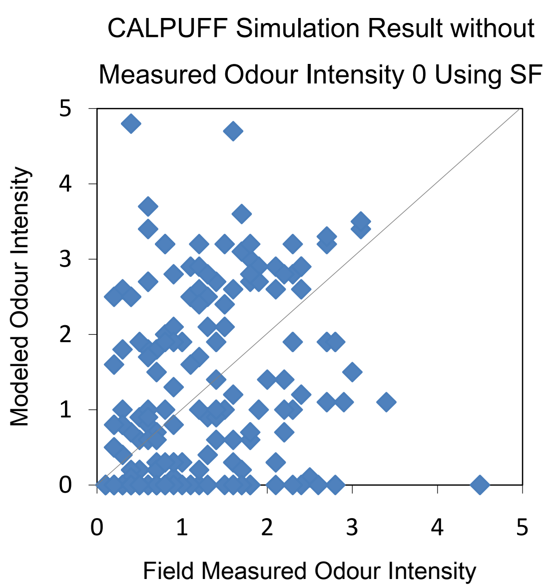


Figure 5.12 CALPUFF predicted and field measured odour intensities (excluding odour intensity 0) using conversion equation from University of Minnesota with scaling factors for Minnesota odour plume data

Table 5.9 Original and adjusted agreement using conversion equation from University of Minnesota for Minnesota odour plume data (excluding measured intensity 0)

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	100	17.2	24.8
	200	28.6	36.6
	300	0	23.2
	Overall	17.6	27.7
CALPUFF	100	18.5	29.4
	200	39.3	47.3
	300	7.1	5.1
	Overall	20.7	30.1

It is shown in the Table 5.9 the increase was 7.6, 8.0 and 23.2% at distance of 100, 200 and 300m for AERMOD, respectively. For CALPUFF, the increase was 10.9, 8.0% at distance of 100 and 200 m respectively. However, agreement decreased 2.0% at distance of 300 m fro CALPUFF. The overall agreement increased 10.1 and 9.4 % for AERMOD and CALPUFF, respectively. Based on this result, it may be concluded conversion equation from University of Minnesota with scaling factors improved some of the performance of for both models if field measured intensity o was excluded.

Scaling factors for both AERMOD and CALPUFF are listed in Table 5.10 if conversion equation from University of Alberta was applied for Minnesota plume data.

Table 5.10 Scaling factors using conversion equation from University of Alberta for Minnesota odour plume data

Model	Scaling factor	
	Barn	Manure storage
AERMOD	3.5	0.7
CALPUFF	1.4	0.5

Table 5.11 shows the original (before using scaling factors) and adjusted agreement (after applying scaling factors) using conversion equation from University of Albert for Minnesota data.

Table 5.11 Original and adjusted agreement using conversion equation from University of Alberta for Minnesota odour plume data

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	100	35.7	35.1
	200	39.3	40.4
	300	7.1	21.4
	Overall	34.2	35.7
CALPUFF	100	33.8	33.7
	200	28.6	33.6
	300	7.1	12.9
	Overall	31.1	34.3

It is shown in the Table 5.11 the increase was 1.1 and 5.0% at distance of 200 m, 14.3 and 5.8% at distance 300 m for AERMOD and CALPUFF, respectively. However, the decrement was 0.6 and 0.1% at 100 m for AERMOD and CALPUFF, respectively. The overall agreement increased 1.5 and 3.2% for AERMOD and CALPUFF, respectively. Based on this result, it may be concluded conversion equation from University of Alberta with scaling factors did not improve much of the performance of for both models.

Scaling factors for both AERMOD and CALPUFF are listed in Table 5.12 if field measured odour intensity 0 was excluded and conversion equation from University of Alberta was applied for Minnesota plume data.

Table 5.12 Scaling factors using conversion equation from University of Alberta for Minnesota odour plume data (excluding measured intensity 0)

Model	Scaling factor	
	Barn	Manure storage
AERMOD	6.4	0.9
CALPUFF	3.2	0.7

Table 5.13 shows the original (without scaling factors) and adjusted agreement (after applying scaling factors) using conversion equation from University of Alberta for Minnesota plume data if field measured odour intensity 0 was excluded.

Table 5.13 Original and adjusted agreement using conversion equation from University of Alberta for Minnesota odour plume data (excluding measured intensity 0)

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	100	25.2	23.7
	200	39.3	43.6
	300	28.6	29.1
	Overall	27.5	29.4
CALPUFF	100	26.5	24.8
	200	21.4	26.6
	300	28.6	30.2
	Overall	25.9	31.1

From Table 5.13 we can see agreement increased 4.3 and 5.2% at distance of 200 m, 0.5 and 1.6% at distance 300 m for AERMOD and CALPUFF, respectively. However, the decrement was 1.5 and 1.7% at 100 m for AERMOD and CALPUFF, respectively. The overall agreement increased 1.9 and 5.2% for AERMOD and CALPUFF, respectively. Based on this result, we may draw the conclusion conversion equation from University of Alberta with scaling factors did not improve much of the performance of for both models if field measured odour intensity 0 was excluded.

5.3.4 Using an ASTM-Standard Guide for Statistical Evaluation of AERMOD and CALPUFF Performance

Figures 5.13 and 5.14 show the fractional bias analysis results of original and adjusted with scaling factor for both AERMOD and CALPUFF models. It shows in two figures the results of FB analysis are pretty poor for AERMOD using both conversion equations, and poor if using conversion equation of Minnesota for CALPUFF. We can also notice from these two figures if conversion equation from University of Minnesota was employed, use of scaling factor can improve much the performance of both CALPUFF and AERMOD, i.e., both biases of average intensity and standard deviation got much closer to original point. But scaling factor cannot help so much if conversion equation from University of Alberta was used. This statistical evaluation of atmospheric dispersion models' performance was consistent with the previous analysis in chapter 5.5.3 above.

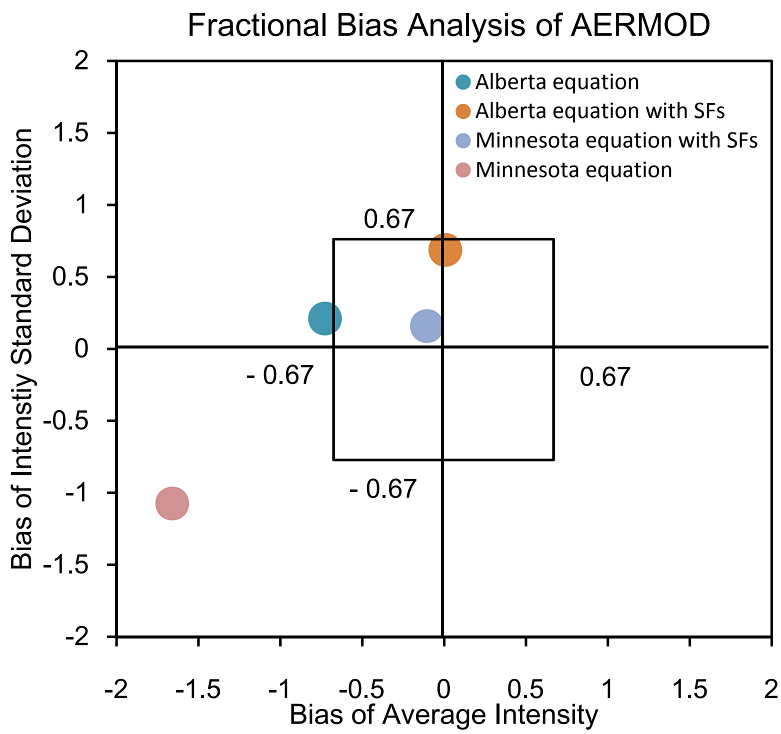


Figure 5.13 Bias analysis results for AERMOD

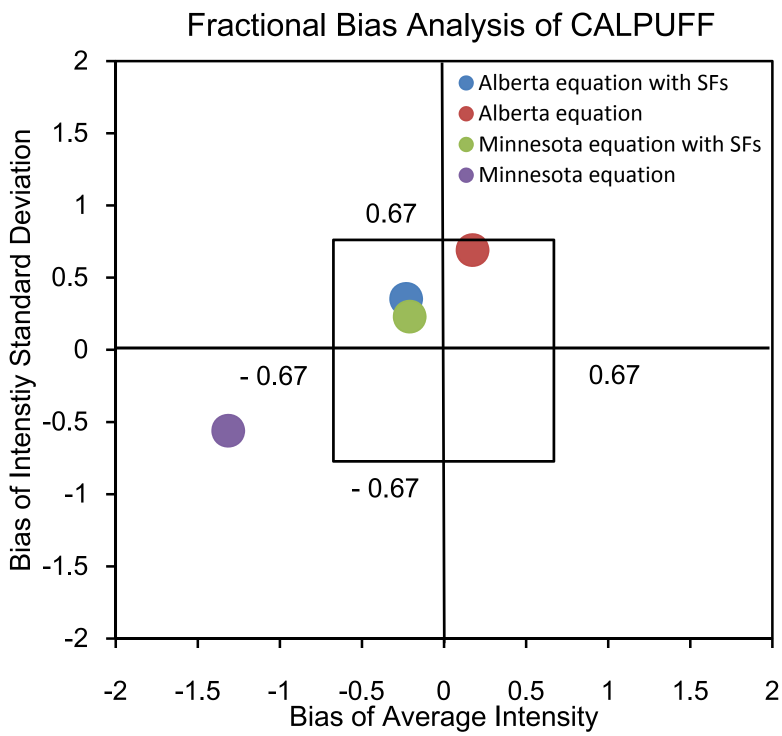


Figure 5.14 Bias analysis results for CALPUFF

5.4 Conclusions

1. CALPUFF got a better agreement of model predicted and field measured odour intensities compared with AERMOD if using conversion equation from University of Minnesota for all field measured Minnesota odour plume data (including measured intensity 0). The difference of agreement between two models was 0.6, 17.9 and 7.1% at distances of 100, 200 and 300 m respectively, and 3.9% for the overall level. Generally, the agreement of the two models for every corresponding distance was close;
2. AERMOD achieved a better agreement of model predicted and field measured odour intensities compared with CALPUFF if conversion equation from University of Alberta was employed for all field measured Minnesota odour plume data (including measured intensity 0). The difference of agreement between two models was 1.9 and 10.7% at distances of 100

and 200 m respectively, and 3.1% for the overall level. The agreement of the two models for every corresponding distance was very close;

3. It was better to choose conversion equation from University of Alberta instead of that from University of Minnesota for Alberta odour plume data considering the result of statistical evaluation of model performance;
4. If field measured odour intensity 0 was excluded from the measured intensities, agreement of modeled and field measured odour intensities went down sharply for both AERMOD and CALPUFF for both conversion equations from University of Minnesota and University and Alberta for Minnesota odour data. Using conversion equation from University of Minnesota, the agreement was 17.6 and 20.7% for AERMOD and CALPUFF, respectively; however, Using conversion equation from University of Alberta, the agreement was 27.5 and 25.9% for AERMOD and CALPUFF, respectively;
5. Agreement of modeled and measured odour intensities for both AERMOD and CALPUFF was poor, not even exceeding 40% for all the measured odour intensities, and not exceeding 30% for the measured odour intensities without intensity 0. The reason may come from three aspects: poor model predictions or poor field measurements or poor of both;
6. Field recorded odour intensities sometimes varied greatly for a single human odour sniffer in one odour measurement session. The reason may be the change of odour intensity during that session or the human-caused error of odour detection;
7. Scaling factors can improve the agreement of predicted and measured odour intensities for both of CALPUFF and AERMOD using conversion equation from University of Minnesota but not conversion equation from University of Alberta. Using conversion equation from University of Minnesota with scaling factors, the overall improvement of agreement was 14.8 and 10.7% for all measured odour intensities and 10.1 and 9.4% for the measured odour intensities without 0 for AERMOD and CALPUFF, respectively. Most of the measured odour intensities were higher than the corresponding modeled ones when using conversion equation from University of Minnesota for Minnesota odour plume data was the reason

scaling factors can be helpful in improving the agreement of modeled and measured odour intensities;

8. Although the scaling factors yielded in this project were not exactly the same as those created by Zhu, (2000), they fell in the same range. The reason of discrimination between them may be Zhu, (2000) used a different model (INPUFF-2);
9. It was better to choose conversion equation from University of Minnesota instead of that from University of Alberta for Minnesota odour plume data from statistical evaluation results of model performance point of view.

6. EVALUATION OF AERMOD AND CALPUFF FOR ODOUR DISPERSION USING FIELD MEASURED ODOUR DATA: PART II. USING ODOUR PLUME MEASUREMENT DATA FROM UNIVERSITY OF ALBERTA

6.1 Introduction

Original field odour measurement data could only be accessible from University of Minnesota, University of Alberta, University of Manitoba and University of Saskatchewan in North America till now. However, odour plume data from University of Alberta were the only data not used by Xing, (2006) to evaluate four air dispersion models. Xing, (2006) served as the first part of a project, and this research will serve as the other part. Qu et al. (2006) employed field measured odour data from University of Alberta to calibrate ISC-PRIME model for odour dispersion simulation and found the model predicted odour intensities were 1 to 2 magnitudes more than the corresponding measured odour intensities though the trend of odour sniffers measured field odour intensities was similar to the model predicted ones.

Field odour measurement data from University of Alberta was used in this part to evaluate the capability of AERMOD and CALPUFF in predicting odour concentrations downwind a selected farm in Alberta. Scaling factors were developed to improve the agreement of modeled and measured intensities.

6.2 Materials and Methods

As stated previously in chapter 5, evaluation of models required odour emissions of the odour source(s), field odour data, meteorological data, and terrain condition surrounding the odour source(s). Odour emissions of the odour source(s), field odour data, and meteorological data were obtained by a research team lead by Drs. J. C. Segura and J. J. R. Feddes, researchers of Alberta Agriculture Food and Rural Development (AAFRD), in 2003. Meteorological data were also recorded by odour sniffers involved in that project. A portable weather station was employed in the case that some weather data were missed by the odour sniffer(s) for such a long experiment time.

6.2.1 Site Description and Odour Emission Rates

A swine farm with location of 113.82W (Longitude), 53.31N (Latitude) and elevation of 715 m above MSL in Calmar, Alberta was selected to carry out this project. There were five odour emission sources: three EMS cells and two animal facilities. The east barn was north-west direction and the west one was like a T shape. These barns were mechanically ventilated. The largest EMS cell was located at the northwest corner of the swine farm and a smaller one was located besides it and the third one was parallel to the east barn. The relative position of these five odour sources are shown in Figure 6.1.

Figure 6.1 Air Photo of the selected swine farm Facilities in Calmar, Alberta (adapted from AMEC Earth & Environmental, 2003)

For use in the model, the West Barn was divided into two barns for simplicity sake. West Barn1 is furthest east and runs north south. West Barn 2 runs east west and was furthest west. This was the easiest way to put the coordinate parameters in the model. Actually West Barn 2 had the highest peak and runs east west for the full length of the two barns.

Odour emission rate was measured during the period of August 14th to September 23rd, 2003 for the west barn and lagoon one. Odour emission from east barn was estimated to be the same as west barn basing on the number of animals as compared to the west barn. Emission rate of Lagoon one was measured with a wind tunnel. Lagoon two and three were assumed to have the same average emission rate (OU/s-m^2) as that of lagoon 1. The summary of average odour emission rates from the odour sources are given in Table 6.1.

We can see from Figure 6.1 there are two roads of trees on the farm. One road of trees is on the west side of the farm lane. These trees extend from the county road to the west barn on the west side of the farm lane with almost constant height about 13.3 m for the full length. The other road of trees is on the east side of farm lane. These trees extended from the county road to the private road with almost constant height about 15.2 m for the full length. Field within short distance (<

600 m) surrounding the farm is the flat cropland. There is a tree belt standing about 600 m away from the farm, the tress formed a circle embracing three sides of the farm, i.e., east, north and west sides of the farm. These trees will certainly affect odour dispersion.

Table 6.1 Odour emission rates of buildings and earthen manure storages from the swine farm in Calmar, Alberta (Segura and Morin, 2003)

Date	Building odour emissions			EMS odour emissions			
	Total odour emissions (OU/S)		Odour emission rate (OU/S-m^2)	Total odour emissions (OU/S)			Odour emission rate (OU/S-m^2)
	West barn	East barn		Lagoon 1	Lagoon 2	Lagoon 3	
08/14/03	84508	63381	20.9	1067785	161674	152124	62.0
08/21/03	43284	32463	10.7	161454	24446	23002	9.4
08/26/03	68516	51387	17.0	113769	17226	16208	6.6
08/28/03	56162	42121	13.9	157900	23908	22496	9.2
09/02/03	86767	65075	21.5	184007	27861	26215	10.7
09/04/03	55346	41510	13.7	410748	62192	58518	23.9
09/09/03	53644	40233	13.3	1415473	214319	201658	82.2
09/11/03	29711	22283	7.4	224466	33987	31979	13.0
09/16/03	54692	41019	13.5	781193	118281	111294	45.4
09/18/03	72184	54138	17.9	79953	12106	11391	4.6
09/23/03	9736	7302	2.4	231360	35031	32961	13.4

6.2.2 Field Odour Plume Measurement

As described in Segura and Morin (2003), an odour sniffer panel consisting of five trained persons was assigned to collect the field data downwind emission sources in August and September, 2003. This sniffer panel used handhold personal global position system (GPS) units to locate themselves approximately downwind the odour source according the wind direction, which could be obtained via a radio link between them and weather station. Intensity scales of 0 - 8 (0: no odour; 1: not annoying; 2: a little annoying; 3: a little annoying; 4: annoying; 5: annoying; 6: very annoying; 7: very annoying; 8; extremely annoying) with constant interval of 1 was used by the odour sniffers to assess the odour they detected. Every data collection session lasted 8 minutes, and during this period of time each person recorded his/her measurement per minute. Thus, during a data collection session, 8 records were obtained from each odour sniffer. The average of these 8 records was deemed as the final odour intensity that sniffer got at that period of odour sniffing activity at that specific location. A total of 52 sessions (258 pairs) of data over 11 days were taken. The detailed procedure how to measure the odour was presented at Segura and Morin (2003).

Weather condition parameters like wind speed and direction, temperature, etc. were recorded at the same time when the odour intensity was written down. The weather station on the farm was also employed to record the weather data. The averaged value of each weather condition parameter in that session was deemed as the weather condition of that session and was prepared for the input of air dispersion models.

6.2.3 Model Configuration

AERMOD of version 02222 and CALPUFF of version 5.7 were used in this part. Most of the configurations of two models were the same as those addressed in chapter 4.2.4 of models configuration; however, some there were still some differences should be specified based on simulation situation in this part. The differences were:

a) Simulation time was changed to correspond the time field odour data were taken;
b) Odour emission rates were prepared according to Table 6.1;
c) The elevation of the simulated area was 715 m;
d) Field measured meteorological data in this part were used here;
e) The type of odour receptors was discrete receptors, and the location of these receptors were specified according to the location of human sniffers involved in this part that stood in the field to sniff and record the odour intensity;

f) For the upper air data used in AERMOD, The location of the nearest upper air station was 114.06W (Longitude), 53.33N (Latitude);

g) For CALPUFF, the land type within the short distance (< 600 m) was set to unirrigated agricultural land, and the corresponding value of surface roughness length was 0.20 in both August and September according to Table 4.5. However, the land type for long distance (>= 600 m) was set to forest land and the corresponding value of surface roughness length was 1.30 in both August and September according to Table 4.5;

h) For AERMOD, the values of three parameters, i.e., Albedo, Bowen ratio, and surface roughness, varied according to the corresponding seasons of the year and the distance to the odour sources. According to Tables 4.3 to 4.5, the value of Albedo, Bowen ratio, and surface roughness was set to 0.20, 0.5, and 0.20 in both August and September within the short distance (< 600 m). However, for those field odour data taken in or out of tree belt (>= 600 m), the value of Albedo, Bowen ratio, and surface roughness was set to 0.12, 0.3, and 1.3 in both August and September.

6.2.4 Relationship between Odour Concentration and Intensity

Both concentration-intensity conversion equations from University of Alberta and University of Minnesota were used in this part to convert modeled concentrations to intensities to be compared with corresponding field measured intensities. For the conversion equation from University of Alberta, i.e., equation 2.3, 8-point scales were used; while for the conversion equation from University of Minnesota, i.e., equations 2.1 and 2.2, 5-point scales were used.

6.2.5 Comparison between Model Predictions and Field Measurement

A total of 258 pairs of data (including field measured intensity 0) were compared between the model predictions and field measurements for both models respectively. As stated previously, the measured odour intensities in this part used 8-point referencing scales. The model predicted concentrations were converted to intensities using conversion equations of University of Alberta and University of Minnesota. Procedures and methods of comparing (matching/mismatching) the modeled intensities and corresponding measured intensities were addressed in details in chapter 5.2.5.

In order to analyze the impact of field measured odour intensity 0 on the agreement of modeled and field measured odour occurrences, all field measured odour intensity 0 was excluded. The method of picking out the measured intensity 0 was addressed in details in chapter 5.2.5. According to the statistical results of Alberta field measured odour intensities, there were 19 sessions in which all measured odour intensities were 0, i.e., only 239 pairs of data could be compared if excluding field measured intensity 0.

6.3 Results and Discussions

Evaluation of AERMOD and CALPUFF through comparing model predicted and field measured odour intensities to find out the agreement between them was presented in this part. Model predicted concentrations were converted to corresponding intensities using concentration-intensity conversion equations. Scaling factors were also used to improve the agreement. Discussions of the simulated results as well as statistical evaluation of two models performance using an ASTM-Standard Guide were also made.

6.3.1 Evaluating Models Using Concentration-intensity Conversion Equation from University of Alberta

It is obviously noticed in Table 2.2 the concentration values for intensities 1, 2, and 3 ranged 0 – 12 OU/m^3. Because it is difficult for human noses to distinguish the difference of concentrations under 25 OU/m^3 (SRF Consulting Group, Inc., 2004), intensities 1, 2 and 3 were grouped into the same intensity level, i.e., intensity 1 - 3. The originally field recorded odour intensities were then categorized to seven grades, i.e., 0, 1 - 3, 4, 5, 6, 7 and 8. The converted intensities from concentrations predicted by models also took these seven grades.

Figures 6.2 and 6.3 presented the detailed information of modeled versus measured odour intensities using the conversion equation from University of Alberta for Alberta odour plume data. The way to produce these two figures was the same as the way to create Figures 5.1 and 5.1 in chapter 5.3.1, except that there were a total of 258 pairs of data. The straight line of X = Y in the figure was drawn to see how many dots were on it. Those dots converging on X = Y means modeled and measured intensities were the same. It could be easily noticed 258 dots scatter at the whole 5 by 5 unit area, and widely two sides of the straight line of X = Y, indicating the agreement of modeled and measured intensities could be pretty low.

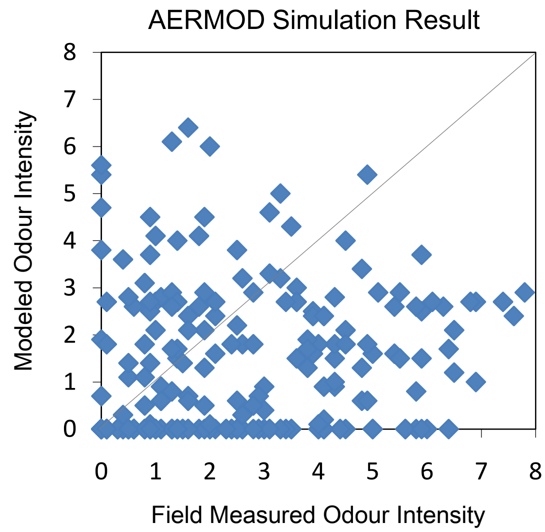


Figure 6.2 AERMOD predicted and field measured odour intensities using conversion equation from University of Alberta for Alberta odour plume data

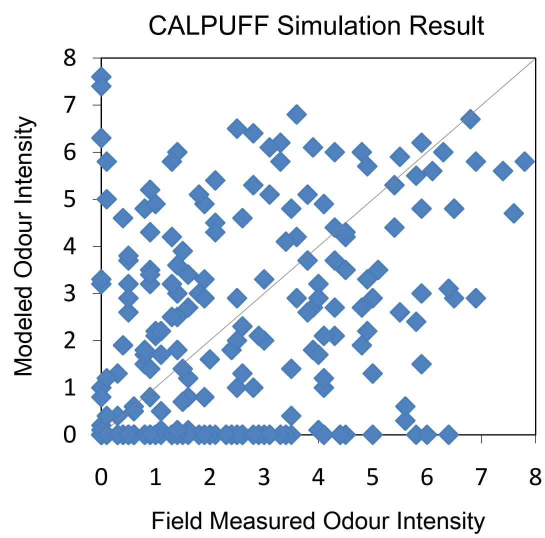


Figure 6.3 CALPUFF predicted and field measured odour intensities using conversion equation from University from Alberta for Alberta odour plume data

Table 6.2 summarized the agreements at distances 200, 300, 500 and 800 m downwind the odour sources after the predicted odour concentrations were converted to intensities using the conversion equation from University of Alberta for these two models.

Table 6.2 Agreement between model predictions and field measurements using conversion equation from University of Alberta for Alberta plume data

Model	Distance (m)	Total NO. of paired data	Agreement NO. of paired data	Agreement Percentage (%)
AERMOD	200	10	1	10.0
	300	44	5	11.4
	500	124	31	25.0
	800	80	25	31.3
	Overall	258	62	24.0
CALPUFF	200	10	6	60.0
	300	44	3	6.8
	500	124	31	25.0
	800	80	20	25.0
	Overall	258	60	23.3

From Table 6.2 above we can see the agreement between model predictions and field measurements for both models pretty low and close for every single distance except for distance of 200 m. The agreement discrimination was 50, 4.6, 0 and 6.3% at the distance of 200, 300, 500 and 800 m for AERMOD and CALPUFF, respectively. The overall agreement discrimination between two models was 0.7%. It could also be seen agreements of model predictions and measurements for both models were ugly. Most of the agreement percentages were around 25%, and the overall agreement percentages were 24.0 and 23.3% for AERMOD and CALPUFF, respectively. Detailed agreement analysis of measured and predicted odour intensities are shown in Tables D.5 and D.6 in Appendix D. From Tables D.5 and D.6, we can notice modeled intensity were higher than the corresponding field measured ones at some intensity levels, and lower at others intensity levels, i.e., there are some values in the unit table above blue background unit tables, and others are below the blue background unit tables. This phenomenon was consistent with the scatting of the dots at two sides of line X = Y in Figures 6.2 and 6.3.

However, if we only consider the measurements with odours detected, i.e., excluding all the odour measurements with intensity zero, the agreement of the modeled and measured intensities was then given in Table 6.3. Figures 6.4 and 6.5 show the detailed information of predicted versus measured intensities using conversion equation from University of Alberta if field measured odour intensity o was excluded.

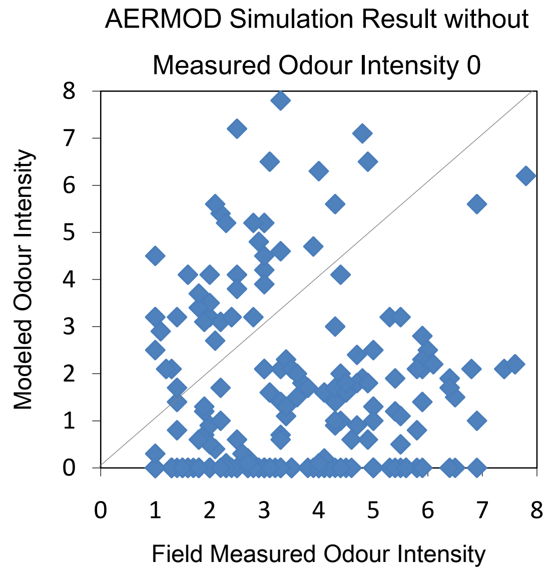


Figure 6.4 AERMOD predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Alberta for Alberta plume data

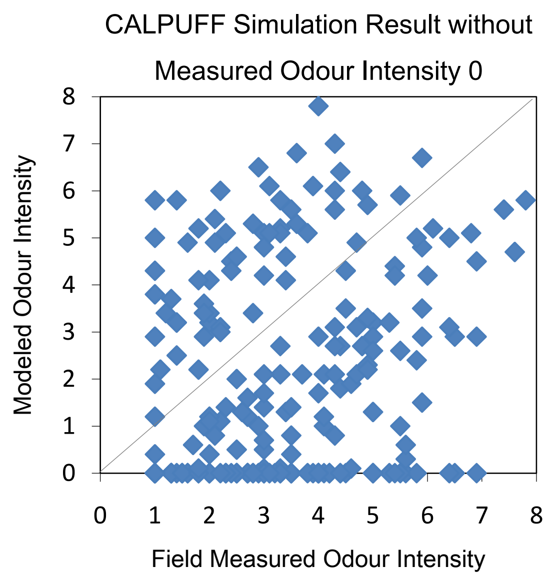


Figure 6.5 CALPUFF predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Alberta for Alberta plume data

Table 6.3 Agreement between model predictions and field measurements (excluding measured intensity 0) using conversion equation from University of Alberta for Alberta plume data

Model	Distance (m)	Total NO. of paired data	Agreement NO. of paired data	Agreement Percentage (%)
AERMOD	200	10	0	0
	300	43	3	7.0
	500	115	13	11.3
	800	71	12	17.0
	Overall	239	28	11.7
CALPUFF	200	10	2	20.0
	300	43	2	4.7
	500	115	15	12.2
	800	71	10	14.1
	Overall	239	29	12.1

From Table 6.3 it could be observed the overall agreement of modeled and measured odour intensities was 14.6 and 13.8% for AERMOD and CALPUFF respectively. Comparing Table 6.2 and 6.3, we can see if intensity zero was not considered, the overall agreement decreased sharply, indicating intensity zero contributed a lot to improve the agreement as shown in Table 6.2.

6.3.2 Evaluating Models Using Concentration-intensity Conversion Equation from University of Minnesota

Figures 6.6 and 6.7 presented the detailed information of modeled versus measured odour intensities using the conversion equation from University of Alberta for Alberta odour plume data. From Figures 6.6 and 6.7 we can obviously notice most of the dots are under the straight line X = Y, indicating most of the modeled odour intensities are lower than the corresponding field measured intensities. It could also be observed a large part of dots converge at zero level of the modeled intensity, showing the models predicted concentrations were very low though the measured intensities fell in the range of 0 to 8.

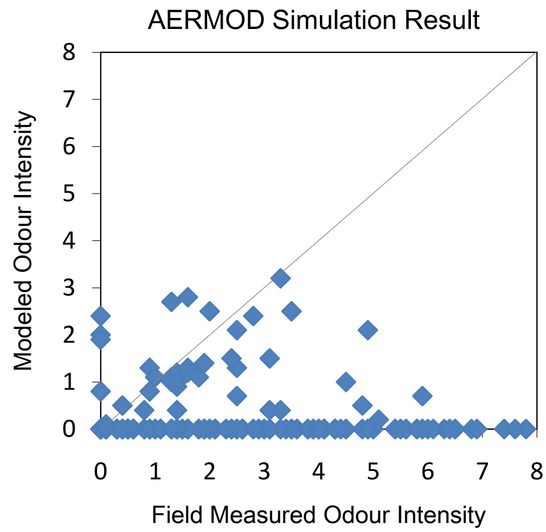


Figure 6.6 AERMOD predicted and field measured odour intensities using conversion equation from University of Minnesota for Alberta odour plume data

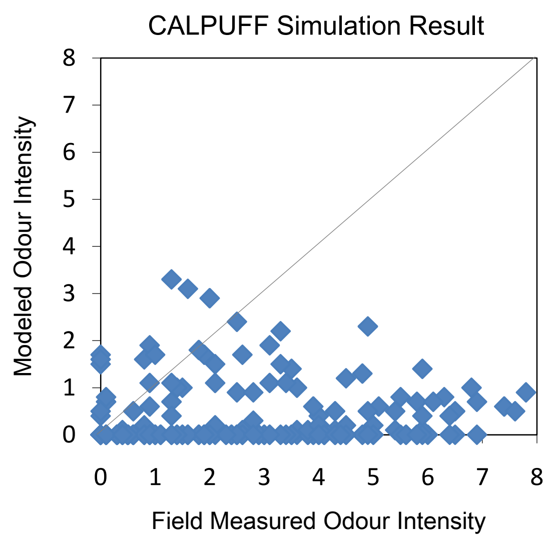


Figure 6.7 CALPUFF predicted and field measured odour intensities using conversion equation from University of Minnesota for Alberta odour plume data

Table 6.4 presented the agreements of modeled versus measured odour intensities using conversion equation from University of Minnesota for Alberta odour plume data for these two models.

Table 6.4 Agreement between model predictions and field measurements using conversion equation from University of Minnesota for Alberta odour plume data

Model	Distance (m)	Total NO. of paired data	Agreement ON. of paired data	Agreement Percentage (%)
AERMOD	200	10	0	0
	300	44	3	6.8
	500	124	31	25.0
	800	80	24	30.0
	Overall	258	58	22.5
CALPUFF	200	10	0	0
	300	44	2	4.6
	500	124	30	24.2
	800	80	23	28.8
	Overall	258	55	21.3

Table 6.4 almost showed the same thing of agreement between model predictions and field measurements for both models as that in Table 6.2, .i.e., the agreement percentage was pretty low and very close for every corresponding distance for two models. The agreement difference was 0, 2.2, 0.8 and 1.2 and at distance of 200, 300, 500 and 800 m respectively. And the agreement difference was 1.2% for the overall agreement level. Agreement percentage analysis of both models was ugly, 22.5 and 21.3% for the overall agreement level for AERMOD and CALPUFF, respectively. Detailed agreement analysis of measured and predicted odour intensities are in Table D.1 and D.2 in Appendix D. we can see from these two tables most of the values are above the blue background unit tables, indicating models under-predicted field measurements. From Tables 6.2 and 6.4, we may draw the conclusion neither of conversion equation from University of Alberta nor conversion equation from University of Minnesota behaved well for the Alberta odour plume data. Generally speaking, the agreement of predicted and measured odour intensities using Alberta odour plume data only barely exceeded 20%, much lower than that of University of Minnesota odour plume data simulation.

If we only consider the measurements with odours detected, the agreement of the modeled and measured intensities was then given in Table 6.5. Figures 6.8 and 6.9 show the detailed information of predicted versus measured intensities using conversion equation from University of Minnesota if field measured odour intensity 0 was excluded.

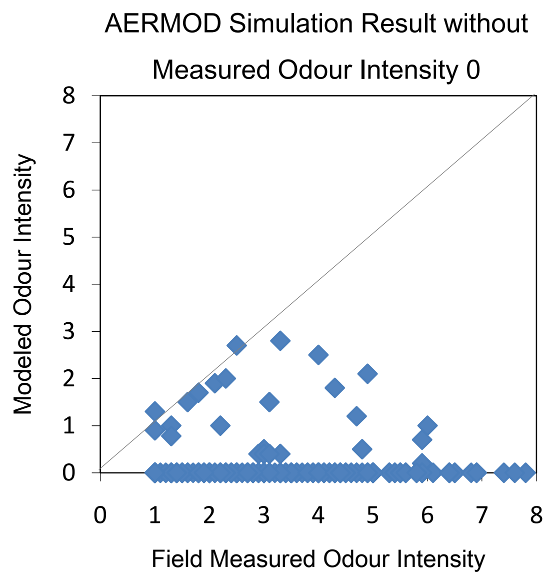


Figure 6.8 AERMOD predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota for Alberta odour plume data

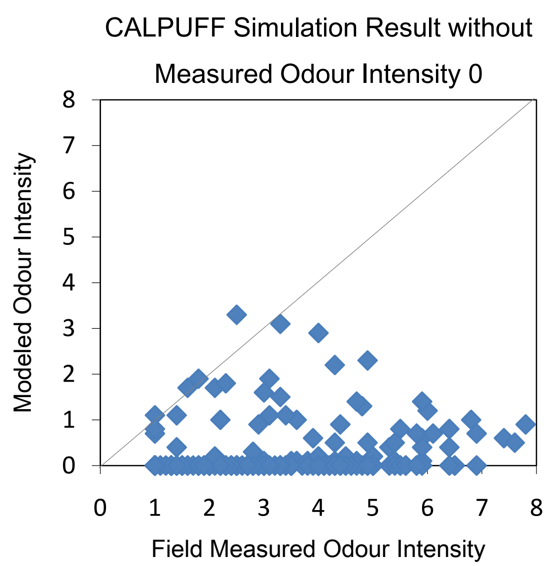


Figure 6.9 CALPUFF predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota for Alberta odour plume data

Table 6.5 Agreement between model predictions and field measurements (excluding measured intensity 0) using conversion equation from University of Minnesota for Alberta plume data

Model	Distance (m)	Total NO. of paired data	Agreement ON. of paired data	Agreement Percentage (%)
AERMOD	200	10	0	0
	300	43	1	2.3
	500	115	15	13.0
	800	71	13	18.3
	Overall	239	29	12.1
CALPUFF	200	10	0	0
	300	43	1	2.3
	500	115	14	12.2
	800	71	10	14.1
	Overall	239	27	11.3

From Table 6.5 it could be observed the overall agreement of modeled and measured odour intensities was 12.1 and 11.3% for AERMOD and CALPUFF respectively. Comparing Table 6.4 with 6.5, we can see if intensity zero was not considered, the overall agreement decreased sharply, indicating intensity zero contributed much to improving the agreement as shown in Table 6.4.

6.3.3 Adjusting Modeled Results Using Scaling Factors

Scaling factors for both AERMOD and CALPUFF are listed in Table 6.6 if conversion equation from University of Alberta was applied for Alberta odour data. Table 6.7 shows the original (without scaling factors) and adjusted agreement (after applying scaling factors) using conversion equation from University of Alberta for Alberta odour data.

Table 6.6 Scaling factors using conversion equation from University of Alberta for Alberta plume data

Model	Scaling factor	
	Barn	Manure storage
AERMOD	7	3.5
CALPUFF	4.5	2

Table 6.7 Original and adjusted agreement after applying scaling factors using conversion equation from University of Alberta for Alberta plume data

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	200	10.0	0
	300	11.4	6.8
	500	25.0	29.0
	800	31.3	31.3
	Overall	24.0	24.8
CALPUFF	200	60.0	10.0
	300	6.8	13.6
	500	25.0	26.6
	800	25.0	40.0
	Overall	23.3	27.9

From Table 6.7 we can see use of scaling factors did not improve much of agreement of modeled and measured odour intensities. For AERMOD, agreement improved 4.0% at distance of 500 m while decreased 10 and 4.6% at distance of 200 and 300 m, respectively. For CALPUFF, agreement improved 6.8, 1.6 and 15% at distance 300, 500 and 800 m, respectively, while decreased 50% at distance of 200 m. The overall increase was 0.8 and 4.6% for AERMOD and CALPUFF, respectively. We may conclude based on the results from Table 6.7 that scaling factors were not helpful if conversion equation from University of Alberta was used for Alberta odour plume data. This conclusion could be consolidated by Figures 6.2 and 6.3. As it was stated in chapter 6.3.1 that dots scatter the whole 8 by 8 unite area, indicating scaling factors can't make them converge on the straight line X = Y.

Scaling factors for both AERMOD and CALPUFF are listed in Table 6.8 if conversion equation from University of Alberta was applied for Alberta odour data and field measured odour intensity 0 was excluded. Table 6.9 shows the original (without scaling factor) and adjusted agreement (after applying scaling factors) using conversion equation from University of Alberta for Alberta odour data if field measured odour intensity 0 was excluded.

Table 6.8 Scaling factors using conversion equation from University of Alberta for Alberta plume data (excluding measured intensity 0)

Model	Scaling factor	
	Barn	Manure storage
AERMOD	10.2	6.4
CALPUFF	5.6	4.5

Table 6.9 Original and adjusted agreement after applying scaling factors using conversion equation from University of Alberta for Alberta plume data (excluding measured intensity 0)

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	200	0	4.5
	300	7.0	5.4
	500	11.3	17.0
	800	17.0	18.4
	Overall	11.7	16.1
CALPUFF	200	20.0	30.0
	300	4.7	5.2
	500	12.2	15.7
	800	14.1	13.7
	Overall	12.1	14.4

From Table 6.9 we can see use of scaling factors did not improve much of agreement of modeled and measured odour intensities. Foe AERMOD, agreement improved 4.5, 5.7, and 1.4% at distance of 200, 500 and 800m, respectively, while decreased 1.6% at distance of 300. However, foe CALPUFF, agreement improved 10, 0.5 and 3.5% at distance 200, 300 and 500 m, respectively, while decreased 0.4% at distance of 800 m. The overall agreement increase was 4.4 and 2.3% for AERMOD and CALPUFF, respectively. We may conclude based on the results from Table 6.7 that scaling factors were not helpful very much if conversion equation from University of Alberta was used for Alberta odour plume data and field measured odour intensity 0 was excluded.

Scaling factors for both AERMOD and CALPUFF are listed in Table 6.10 if conversion equation from University of Minnesota was used for Alberta odour plume data.

Table 6.10 Scaling factors using conversion equation from University of Minnesota for Alberta plume data

Model	Scaling factor	
	Barn	Manure storage
AERMOD	15.5	5
CALPUFF	10.5	9

Figures 6.10 and 6.11 show the detailed agreement information of predicted versus measured intensities using conversion equation from University of Minnesota for Alberta plume data. Compared the locations of dots in Figures 6.6 and 6.7, they converged some to the straight line X = Y in Figures 6.10 and 6.11, indicating scaling factors should be helpful to improve the agreement of modeled and measured odour intensities though the help may be limited.

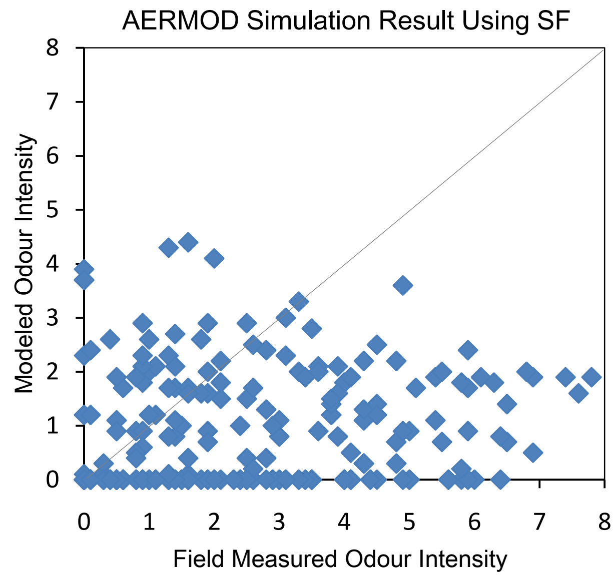


Figure 6.10 AERMOD predicted and field measured odour intensities using conversion equation from University of Minnesota for Alberta plume data

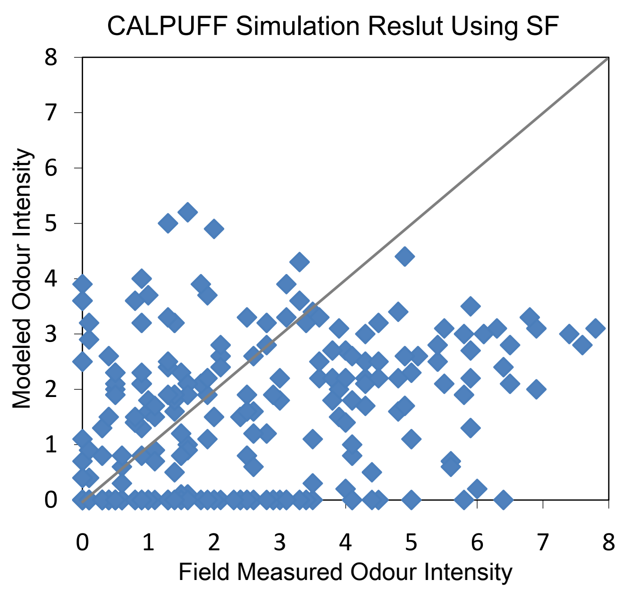


Figure 6.11 CALPUFF predicted and field measured odour intensities using conversion equation from University of Minnesota for Alberta plume data

Table 6.11 summarized the agreement for two models original (without scaling factors) and adjusted agreement (after applying scaling factors) using conversion equation from University of Minnesota for Alberta odour data.

Table 6.11 Original and adjusted agreement after applying scaling factors with conversion equation from University of Minnesota for Alberta plume data

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	200	0	0
	300	6.8	12.1
	500	25.0	28.3
	800	30.0	37.5
	Overall	22.5	29.6
CALPUFF	200	0	10
	300	4.6	10.1
	500	24.2	29.2
	800	28.8	38.3
	Overall	21.3	28.7

From Table 6.11 we can see there were some improvements for every distance after applying scaling factors for both models. The improvement was 5.3 and 5.6%, 3.3 and 5.0%, 7.5 and 9.5% for at distance of 300, 500 and 800 m for AERMOD and CALPUFF, respectively. The improvement was 10% at the distance of 100 m for CALPUFF; however, there was not improvement for AERMOD at this distance. The overall improvement was 7.1 and 7.4% for the AERMOD and CALPUFF respectively. Improvement of agreement for two models after using scaling factors shown in the Table 6.11 was consistent with conclusion came from analysis of Figures 6.10 and 6.11 that dots converged some to the line X = Y.

Scaling factors for AERMOD and CALPUFF are listed in Table 6.12 if conversion equation from University of Minnesota was used for Alberta odour plume data and at the same time field measured odour intensity 0 was excluded.

Table 6.12 Scaling factors using conversion equation from University of Minnesota for Alberta plume data (excluding measured intensity 0)

Model	Scaling factor	
	Barn	Manure storage
AERMOD	23.8	7.2
CALPUFF	12.4	9.5

Figures 6.12 and 6.13 show the detailed agreement information of predicted versus modeled intensities using conversion equation from University of Minnesota for Alberta plume data (excluding measured intensity 0). Compared with the locations of dots in Figures 6.8 and 6.9, they converged a some to the straight line X = Y in Figures 6.10 and 6.11, indicating scaling factors should be helpful to improve the agreement of modeled and measured odour intensities though the help may be limited.

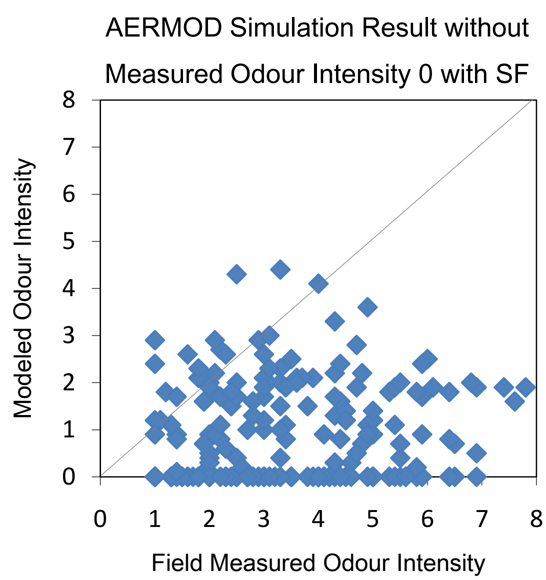


Figure 6.12 AERMOD predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota with scaling factors for Alberta plume data

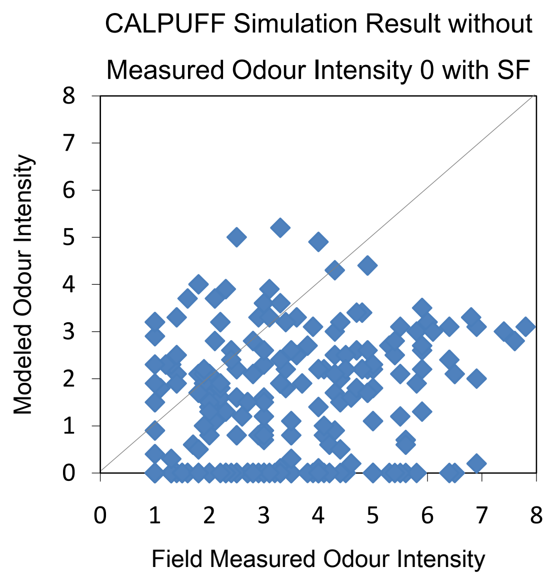


Figure 6.13 CALPUFF predicted and field measured odour intensities (excluding measured intensity 0) using conversion equation from University of Minnesota with scaling factors for Alberta plume data

Table 6.13 summarized the agreement for two models original (without scaling factors) and adjusted agreement (after applying scaling factors) using conversion equation from University of Minnesota for Alberta odour data if the field measured odour intensity 0 was excluded.

Table 6.13 Original and adjusted agreement after applying scaling factors using conversion equation from University of Minnesota for Alberta odour data (excluding measured intensity 0)

Model	Distance (m)	Agreement percentage (%)	
		Original	Adjusted
AERMOD	200	0	10.0
	300	2.3	5.3
	500	13.0	25.5
	800	18.3	17.6
	Overall	12.1	22.5
CALPUFF	200	0	20.0
	300	2.3	8.3
	500	12.2	20.5
	800	14.1	13.1
	Overall	11.3	20.4

From Table 6.13 we can see there were some improvements for every distance after applying scaling factors for both models if field measured odour intensity 0 was excluded. The improvement was 10.0 and 20.0%, 3.0 and 6.0%, 12.5 and 8.3% at distance of 200, 300 and 500 m for AERMOD and CALPUFF, respectively. However, the agreement decreased by 0.7 and 1.0% at distance of 800 m for the AERMOD and CALPUFF, respectively. The overall improvement of agreement was 10.4 and 9.1% for AERMOD and CALPUFF, respectively. Improvement of agreement for two models after using scaling factors without field measured intensity 0 shown in the Table 6.13 was consistent with conclusion came from analysis of Figures 6.12 and 6.13 that dots converged some to the line X = Y compared with those in Figures 6.8 and 6.9.

6.3.4 Using an ASTM-Standard Guide for Statistical Evaluation of AERMOD and CALPUFF Performance

Figure 6.14 and 6.15 show the bias analysis result for these two models. We can see for both models the agreement of measured and predicted odour intensity was really poor if using conversion equation from University of Minnesota. There was some improvement if scaling factors was applied for this conversion equation. Application of scaling factor for conversion equation from University of Alberta could bring improvement but not that distinct.

Either conversion equation from University of Alberta or University of Minnesota could be used for Alberta odour plume data if just looking from the agreement of measured and predicted odour intensities. We may draw another conclusion from the aspect that if we check the bias analysis results for these two models. These two figures show clearly both of the average intensity and intensity standard deviation were smaller if Alberta conversion equation was applied. From this point of view we may say it is better to use conversion equation from University of Alberta when conduct simulation using Alberta odour plume data.

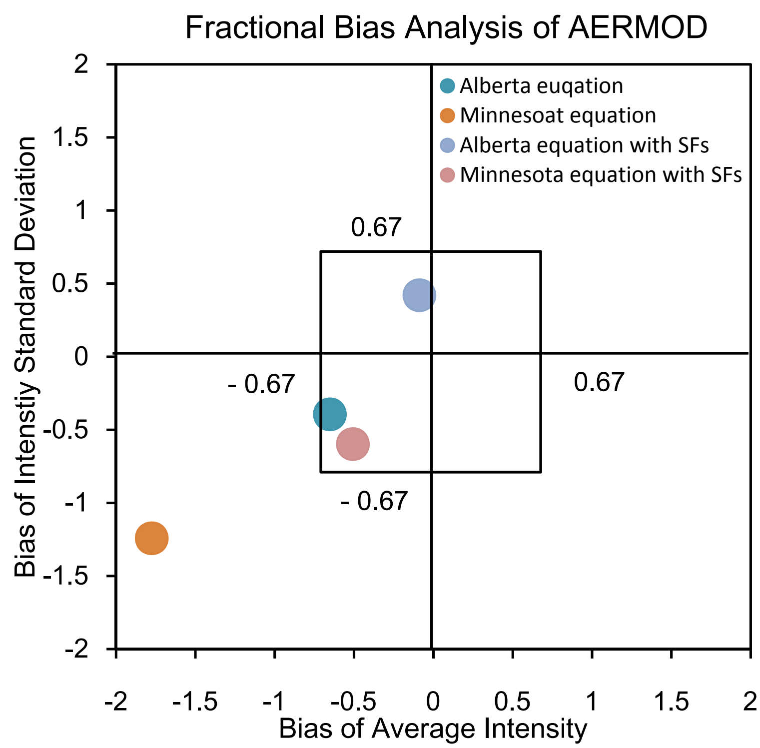


Figure 6.14 Bias analysis results for AERMOD

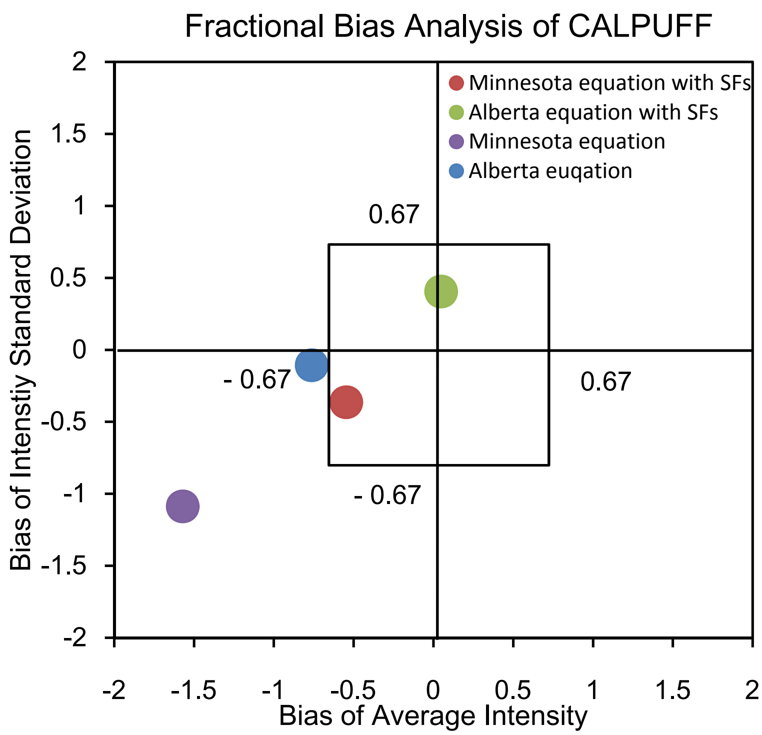


Figure 6.15 Bias analysis results for CALPUFF

6.4 Conclusions

1. AERMOD achieved better agreement of modeled and measured odour intensities compared with CALPUFF using both conversion equations from University of Minnesota and University of Alberta though the differences were limited for all measured odour intensities. The difference for the overall level between two models was 0.7% using conversion equation from University of Minnesota and 1.2% using conversion equation from University of Alberta;
2. Both of conversion equations from University of Alberta and University of Minnesota could be used to convert models predicted odour concentrations to intensities if only considering the agreement analysis results of predicted and measured odour intensities for all measured

odour intensities. The difference under two conversion equations was 1.5 and 2.0% at overall level for AERMOD and CALPUFF, respectively;

3. If field measured odour intensity 0 was excluded from the measured intensities, agreement of modeled and field measured odour intensities decreased greatly for both AERMOD and CALPUFF for both conversion equations from University of Minnesota and University and Alberta for Alberta odour data. Using conversion equation from University of Alberta, the agreement was 11.7 and 12.1% for AERMOD and CALPUFF, respectively; however, using conversion equation from University of Minnesota, the agreement was 12.1 and 11.3% for AERMOD and CALPUFF, respectively;
4. Agreements of modeled and measured intensities for Alberta odour plume data were very low, only barely exceeding 20 and 10% for all measured odour intensities and measurements without intensity 0, which was even lower than those got from Minnesota's odour plume data simulation in chapter 5. The reason may come from poor model predictions or poor field measurements or poor of both. The probability of human-caused reason to low agreement was pretty big because a lot of odour measurements were recorded when the odour sniffers were standing close or in a woods around the farm, making the mistaken records of field odour intensity happen easily;
5. Scaling factor can improve the agreement for both models if conversion equation from University of Minnesota was used. The improvement was 7.1 and 7.4% for all odour measurements, and 10.4 and 9.1% for odour measurements without 0 for AERMOD and CALPUFF, respectively. However, it was not so useful when conversion equation from University of Alberta was applied;
6. Scaling factors generated using conversion equation from University of Minnesota were larger than those created using equation from University of Alberta for field odour measurement data from both University of Minnesota and University of Alberta showed conversion equation from University of Minnesota yielded more conservative values compared with conversion equation from University of Alberta;

7. It was better to choose conversion equation from University of Alberta instead of that from University of Minnesota for Alberta odour plume data from statistical evaluation outcomes of model performance point of view.

7. APPLICATION OF AERMOD AND CALPUFF FOR DETERMINING ODOUR SETBACK DISTANCE FROM A SELECTED SWINE FARM

7.1 Introduction

All of the existing government recommended separation distances, i.e., setback distances, from animal production site to neighboring residential area in the Prairie Provinces, Canada are calculated out through established agricultural odour control guidelines till now. These guidelines have been used by the government to make the decisions in locating new animal production facilities or expanding of existed farms for many years because no other better methods of determining the setbacks were available and plenty of land could be used in the Prairie Provinces. Following the expansion of agricultural industry, less and less land could be accessible for animal production purpose. Based on this situation, scientific methods are needed to deal with determining odour setbacks problem. Air dispersion model is a potential successor of guideline method.

Agricultural odour setbacks guidelines in Canadian Prairie Provinces, i.e., Alberta, Manitoba and Saskatchewan, were used in this part to determine Minimum Separation Distance (MSD) from odour sources to the residential area in the vicinity of these odour sources. Meanwhile, odour dispersion models will be used to predict odour concentrations downwind odour sources. Because the capability of AERMOD and CALPUFF in simulating odour dispersion using field odour measurement data from University of Minnesota and University of Alberta was pretty close, it could not be determined which model is better only from the performance of them in chapters 5 and 6. Subsequently, both of them were used in this part for the purpose of predicting setbacks. Because no universal scaling factors could be available from the research results by other researchers till now and scaling factors developed in chapters 5 and 6 were so different, no scaling factors were applied in this part. This part of the project was intended to use AERMOD and CALPUFF to predict setback distance for a typical sized swine farm in Yorkton, Saskatchewan. The models predicted odour setback distances for this farm were then compared with these three-province guidelines recommended setbacks.

The previous sensitivity analysis revealed that different acceptable odor concentration levels should be used to get the same odour travel distance if steady state and variable weather conditions are used. In this chapter, we took the standard practice that US EPA has been using, i.e., employing historical hourly weather data to get the annual average odour concentrations at the receptors location.

7.2 Odour Setbacks Guidelines of Canadian Prairie Provinces

Odour setbacks guidelines of three Canadian Prairie Provinces, i.e., Saskatchewan, Manitoba and Alberta, were presented in this part. It could be noticed both guidelines of Saskatchewan and Manitoba are very easily follow because they are only based on Animal Units (AUs) of the farm and the neighboring residence scale. However, Alberta odour control guideline was more complicated compared with the previous two because it is based on some complex equations that involve several parameters related to the odour source and odour dispersion condition and topography surrounding the farm.

7.2.1 Saskatchewan Odour Setbacks Guideline

Odour setback distance guideline for establishing and managing livestock operation was mentioned in Saskatchewan Agriculture and Food, (1999). Odour setbacks calculated out by this provincial odour control guideline is quite simple to follow. First, we calculate the total Animal

Units of all animals (e.g., swine, poultry) in the farm. AU is the measurement of any kind of animals in the feeding operation. An AU is "one mature cow of approximately 1000 pounds and a calf up to weaning, usually 6 months of age, or their equivalent" (Saskatchewan Agriculture and Food, 1999). Converting all animals to AUs allows equal standards for all animals based on type and size and manure production. Though swine was the only kind animal involved in this part, they were at different growth phases thus different weight and manure production, so it was necessary to convert them to AUs via the standard unit criterion. Then the setback distance is calculated out by AUs and the neighboring residence area scale. Saskatchewan MSD for odour control is shown in Table 7.1. The general rule was the larger of the residence scale and AUs, the longer of the MSD.

Table 7.1 Saskatchewan recommended minimum separation distance from agricultural odour source to rural residence (Saskatchewan Agriculture and Food, 1999)

Separation Requirements (m)						
Population	Animal Units					
	10 – 50	50 – 300	300 – 500	500 – 2000	2000 – 5000	> 5000
Single Rural Residence	300 – 450	300 – 450	400 – 600	800 – 1200	1200 – 1600	1600 – 2000
< 100	400 - 600	400 – 600	800 – 1200	1200 – 1600	1600 – 2000	2000 – 2400
100 – 500	400 – 600	800 – 1200	1200 – 1600	1600 – 2000	2400 – 2400	2400 – 2400
500 – 5000	800 – 1200	1200 - 1600	1600 – 2000	2400 – 2400	3200 – 3200	3200 – 3200
> 5000	800 – 1200	2400 – 2400	2400 – 2400	3200 – 3200	3200 – 3200	3200 – 3200

Because hog was the only considered kind of animal in Saskatchewan in this part, Table 7.2 was used to convert animal numbers to AUs in Saskatchewan.

Table 7.2 Converting number of animals to Animal Units for Saskatchewan odour guideline (Saskatchewan Agriculture and Food, 1999)

Type	Kind of Animal	Number which equals one animal unit
Hog	Boars or sows	3.0
	Gilts	4.0
	Feeder pigs	6.0
	Weaning pigs	20.0

7.2.2 Manitoba Odour Setbacks Guideline

Manitoba minimum separation distance for reducing odour impact on neighbors was calculated out based on Animal Units of the farm and the type of the residential area as shown in Table 7.3 (Manitoba Agricultural Guidelines Development Committee, 2007). Residential area was generally divided into two groups: single residence and special purposed land use. It needs much longer separation distance for the second group compared with the ordinary residential area for the same farm scale. It could also be observed the distance to the EMS is longer compared to the building for the same level of AUs. The reason for this is normally manure storage cells produced more odour than the animals stored in building in that farm. The maximum number of residences within 1.6 km to the farm was also specified.

Table 7.3 Manitoba recommended minimum separation distance for sitting livestock operations (Manitoba Agricultural Guidelines Development Committee, 2007)

Population	Maximum number of residences within 1.6km[1]	Minimum setback distance (m)			
		From single residence		From designated residential or recreation area[2]	
		To EMS	To building[3]	To EMS	To building
10 – 100	18	200	100	800	530
101 – 200	16	300	150	1200	800
201 – 300	15	400	200	1600	1070
301 – 400	14	450	225	1800	1200
401 – 800	12	500	250	2000	1330
801 – 1600	10	600	300	2400	1600
1601 – 3200	8	700	350	2800	1870
3201 – 6400	6	800	400	3200	2130
6401 – 12800	4	900	450	3600	2400
12801 and grater	2	1000	500	4000	2670

[1]Number of residences within 1.6 km (one mile) of the center of the facility applies only to new facilities. Expansions of existing facilities and the proponent's residence are excluded;

[2]Officially designated areas in a development plan or basic planning statement;

[3]The distance to buildings includes barns and non-earthen manure storages such as above or below grade structures which may be covered or uncovered.

For Manitoba, the table used to convert animals to AUs is listed in following table (Table 7.4). The listed animal in the table is pig, not including other kind of animals because it is the only considered animal in Manitoba in this part.

Table 7.4 Converting number of animals to Animal Units for Manitoba odour guideline (Manitoba Agricultural Guidelines Development Committee, 2007)

Animal Units (AU)	Barn capacity or animal places				
	Sows, Farrow-Finish (110-115 kg)	Sows, Farrow-Weaning (5 kg)	Sows, Farrow-Nursery (23 kg)	Weanlings (5-23kg)	Grower/Finishers (23-113 kg)
10 – 100	8 – 80	32 – 319	40 – 400	303 – 3030	70 – 699
101 – 200	81 – 160	323 – 639	404 – 800	3061 – 6061	706 – 1399
201 – 300	161 – 240	642 – 958	804 – 1200	6091 – 9091	1406 – 2098
301 – 400	241 – 320	962 – 1278	1204 – 1600	9121 – 12121	2105 – 2797
401 – 800	321 – 640	1281 – 2556	1604 – 3200	12152 – 24242	2804 – 5594
801 – 1600	641 – 1280	2559 – 5112	3204 – 6400	24273 – 48485	5601 – 11189
1601 – 3200	1281 – 2560	5115 – 10224	6404 – 12800	48515 – 96970	11196 – 22378
3201 – 6400	2561 – 5210	10227 – 20447	12804 – 25600	97000 – 193939	22385 – 44755
6401 – 12800	5121 – 10240	20450 – 40895	25604 – 51200	193970 – 3878789	44762 – 89510
12801 and grater	10241 and greater	40898 and greater	51204 and greater	387909 and greater	89517 and greater

7.2.3 Alberta Odour Setbacks Guideline

The Alberta MSD is determined by factors such as the Odour Production (*OP*), Odour Objective (*OB*), Dispersion Factor (*DF*), and Expansion Factor (*EF*) as following equation (Alberta Standards and Administration Regulation, 2000):

$$MSD = OP^{0.365} \times OB \times DF \times EF \quad (7.1)$$

<u>Odour Production (*OP*)</u> *OP* measured by Livestock Sitting Units (LSU) is clarified in the Alberta Standards and Administration Regulation, (2000) and parts of LSU table are presented in Table 7.5. There were four factors contributing to *OP*, including the nuisance value of livestock

(*Factor* A_A), technology of production systems (*Factor* B_A), manure production (*MU*), and number of animals as following:

$$OP = LSU = Factor\ A_A \times Factor\ B_A \times MU\ Reciprocal \times number\ of\ animals \quad (7.2)$$

Detailed information of *Factor* A_A, *Factor* B_A, and *MU Reciprocal* for different animals categories are tabulated in the Alberta Standards and Administration Regulation, (2000).

Odour Objective (*OB*) *OB* describes the sensitivity or assumed tolerance level of neighboring land uses. Its value stated in Alberta Standards and Administration Regulation, (2000) was listed as:

Category 1: *OB* = 41.04 for land zoned for agricultural purposes such as farmsteads, acreage residences, etc.

Category 2: *OB* = 54.72 for land zoned for non-agricultural purposes such as country residential, rural commercial businesses, etc.

Category 3: *OB* = 68.40 for land zoned as large scale country residential, high use recreational, or commercial purposes as well as for the urban fringe boundary or land zoned as a rural hamlet, village, or town with an urban fringe.

Category 4: *OB* = 109.44 for land zoned as rural hamlet, village, or town without an urban fringe.

Dispersion factor (*DF*) *DF* permits a variance to *MSD* based on the impact of climatic and terrain on odour dispersion. The standard value is 1.0 (Alberta Standards and Administration Regulation, 2000).

Expansion factor (*EF*) *EF* only applies to the expanding operations.

Table 7.5 Alberta Livestock Sitting Units table (Alberta Standards and Administration Regulation, 2000)

Category of Livestock	Type of Livestock	Factor A_A	Technology Factor B_A	MU
Swine Liquid	Farrow to finish	2.000	1.100	1.780
	Farrow to wean	2.000	1.100	0.670
	Farrow only	2.000	1.100	0.530
	Feeders/Boars	2.000	1.100	0.200
	Growers/Roasters	2.000	1.100	0.118
	Weaners	2.000	1.100	0.055
Swine Solid	Farrow to finish	2.000	0.800	1.780
	Farrow to wean	2.000	0.800	0.670
	Farrow only	2.000	0.800	0.530
	Feeders/Boars	2.000	0.800	0.200
	Growers/Roasters	2.000	0.800	0.118
	Weaners	2.000	0.800	0.055

7.3 Materials and Methods

A typical sized of swine farm located in Yorkton, Saskatchewan was targeted to get odour emissions. 5-year warm season meteorological data of simulated area were used. Odour setback distances predicted by both models AERMOD and CALPUFF as well as the Canadian Prairie Provinces were compared for the three different sites of the farm.

7.3.1 Site Description and Odour Emission Rates

The involved typical sized swine farm consisting of three different farms was located at Yorkton, Saskatchewan. These three farms included one farrowing/gestation site (5,000 sows, 3 barns, one 2-cell EMS), one nursery site (19,200 head, 4 barns, one 2-cell EMS), and one finishing site (11,550 head, 1 barn, one 2-cell EMS) (Guo et al., 2005b). The layout of the farm is shown in

Figure 7.1. The study area was relatively flat crop land and there were no obstacles around the farm. Odour emission rates for the input of models from buildings and EMS of these three sites were measured from May to October, 2003. The geometric means of the odour emission rates measured in those six months were used as the warm season odour emission rates as shown in Table 7.6.

Table 7.6 Warm season emission rates from buildings and EMS from swine farm in Saskatchewan (Guo et al., 2005b)

Odour emission site		Odour emissions of warm season geometric mean (OU/s)	Odour emission rate of warm season geometric mean (OU/s-m^2)
Breeding/Gestation & Farrowing	Building[1]	106377	10.4
	Building[2]	138166	26.7
	Cell	16122	5.5
	Cell	164434	34.5
Nursery	Building	188103	24.0
	Cell	134804	24.0
	Cell	252811	25.8
Finishing	Building	394298	41.3
	Cell	270537	48.1
	Cell	302732	30.9

[1]Emission from Breeding/Gestation;
[2]Emission from Farrowing

7.3.2 Meteorological Data Involved in This Part

Generally, warm season are the high odour occurrence time in one year. The reason for this is high odour emissions are released from buildings and outdoor manure storages during this period of time. To be conservative, instead of getting annual average odour concentrations around the odour source, we choose the worst time of the year, i.e., warm season, to predict odour setback distance in this part. Warm season here is defined from May to October consecutively in one year. To predict setback distance using air dispersion models, US EPA recommends at least five years of meteorological data should be applied. Based on these, 5-year hourly meteorological data from May to October at each year from 1998 to 2002 at this place were used. Model simulations were carried out separately for these five years and the geometric mean of them was deemed as final odour concentrations. Upper air data of these five years used in AERMOD was obtained from the nearest upper air station, Bratts Lakes Upper Air Station, Saskatchewan.

7.3.3 Model Configuration

AERMOD of version 02222 and CALPUFF of version 5.7 were used in this part. Most of the configurations of two models were the same as those addressed in chapter 4.2.4 of models configuration; however, some there were still some differences should be specified based on simulation situation in this part. The differences were:

a) Simulation time was changed to correspond the time field odour data were taken;
b) Odour emission rates were prepared according to Table 7.6;
c) The elevation of the simulated area was 499 m;
d) The type of odour receptors was gridded receptors, and odour receptors were located surrounding the farm with uniform spacing of 100 m;
e) For the upper air data used in AERMOD, The location of the nearest upper air station was 114.10W (Longitude), 53.55N (Latitude);
f) For both AERMOD and CALPUFF, value of surface roughness length was set to 0.20 from May to October according to Table 4.5. For AERMOD, value of Albedo and Bowen ratio was set to 0.20 and 0.5 from May to October respectively according to Table 4.5.

Because the target farm covered too large area for the CALPUFF to run for a single time, CALPUFF was used to simulated odour dispersion for these three sites separately. The results were then put together in one figure. For AERMOD, however, one run for all three sites was adequate.

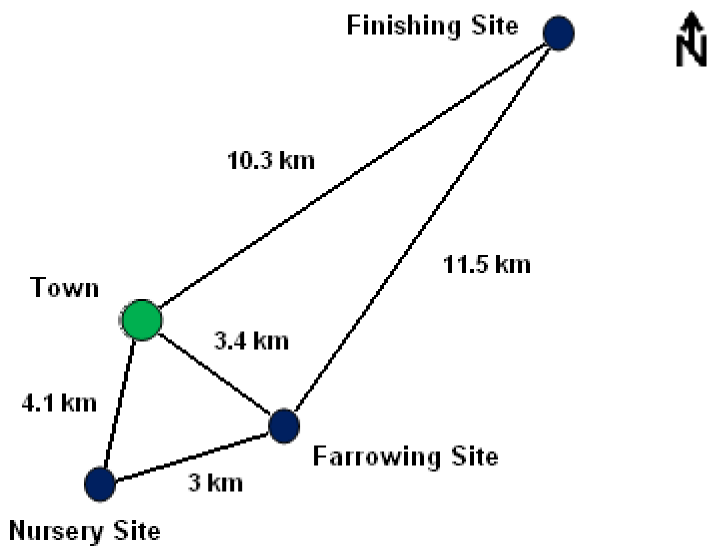


Figure 7.1 Layout of the swine barn in Saskatchewan for the purpose of applying models in setback distance determination (adapted from Guo et al., 2005b)

7.4 Results and Discussions

5-year warm season odour concentration contour maps in the vicinity of the farm as simulated by CALPUFF and AERMOD were shown in Figures 7.2 and 7.3. Though the shape of contours shown in two figures is not exactly the same for each site, the change trend of the contours is similar, i.e., the odour traveled longer at the directions of WNW and SSE for the same concentration level for two figures. According to the statistical calculation result of weather data of this area, the prevailing wind directions of this area are WNW and SSE. It may be concluded odour travel longer distance under leeward of prevailing wind direction, which agreed with what has been found in Guo et al. (2005b) and Xing, (2006). Both of them studied odour occurrence in the same area and found that the areas with high odour events were mostly downwind the prevailing wind directions.

For a certain odour concentration value, there was a maximum odour travel distance and a minimum odour travel distance from the source. Take AERMOD simulation result for the Finishing site as an example, the maximum odour travel distance should be approximately at the direction of WNW, and the minimum odour travel distance approximately at the direction of SSW. The maximum odour travel distance can be used as the maximum odour setback distance from the odour source and the minimum odour travel distance can be used as the minimum odour setback distance. For comparing the setbacks predicted by models and recommended by guidelines, if the guidelines recommended distances are shorter than the minimum setback distance, then there was always odour occurrence; if the guidelines recommended distances were between minimum and maximum setback distance, then there were odour occurrence at sometime and; if the guidelines recommended distances were longer than the maximum setback distance, there was no odour occurrence at all. For the purpose of setting appropriate odour setback distance, the third case should be chosen, i.e., the recommended distances by odour setbacks guideline should be always longer than maximum setback distances.

The maximum and minimum setback distance for field odour concentrations of 1, 2, 5 and 10 OU/m^3 simulated by two models during warm season as well as three Canadian Prairie Provinces odour control guidelines recommended setbacks for three different swine operation sites was presented in Tables 7.7 to 7.9. For the Farrowing site (Table 7.7), we can notice both of Saskatchewan and Manitoba odour control guideline recommended MSD are longer than the maximum setback distance as predicted by both models for all odour concentration levels (1, 2, 5 and 10 OU/m^3). However, Alberta odour control guideline recommended MSD was 1430 m, shorter than maximum setback distance for odour concentration level of 1 OU/m^3 for AERMOD predictions and 1 and 2 OU/m^3 for CALPUFF predictions. For the Nursery site (Table 7.8), the Saskatchewan recommended MSD is longer than the model predicted maximum distance for all tabulated odour concentration values, and Alberta recommended MSD is shorter than model predicted maximum distance for odour concentrations of 1 and 2 OU/m^3, longer than model predicted maximum distance for odour concentrations of 5 and 10 OU/m^3, and Manitoba recommended MSD is shorter than model predicted maximum distance for odour concentrations of 1 OU/m^3, longer than model predicted maximum distance for odour concentrations of 2, 5 and 10 OU/m^3. For the Finishing site (Table 7.9), the Saskatchewan recommended MSD is longer than the model predicted maximum distance for all tabulated odour concentration values except for odour concentration of 1 OU/m^3 predicted by AERMOD, and Alberta recommended MSD is shorter than model predicted maximum distance for odour concentrations of 1 and 2 OU/m^3, longer than model predicted maximum distance for odour concentrations of 5 and 10 OU/m^3, and Manitoba recommended MSD is shorter than model predicted maximum distance for odour concentrations of 1 OU/m^3, longer than model predicted maximum distance for odour concentrations of 2, 5 and 10 OU/m^3.

Now the problem is what odour concentration level should be chosen? There is no a specific odour concentration level that could be accepted by most of the researchers till now; however, some researchers (e.g., Jacobson, et al., 2002; Guo et al., 2005a) did suggest some odour concentration levels and the corresponding desired odour-free-frequency as a criterion of acceptable odour event. An interesting thing could be found from these three Prairie Provinces guidelines suggested odour MSD is that Alberta recommended MSD were much shorter than those recommended by other two provinces for all three swine operation sites. This may come from that Alberta government is less strict with odour related issues compared with other two provincial governments.

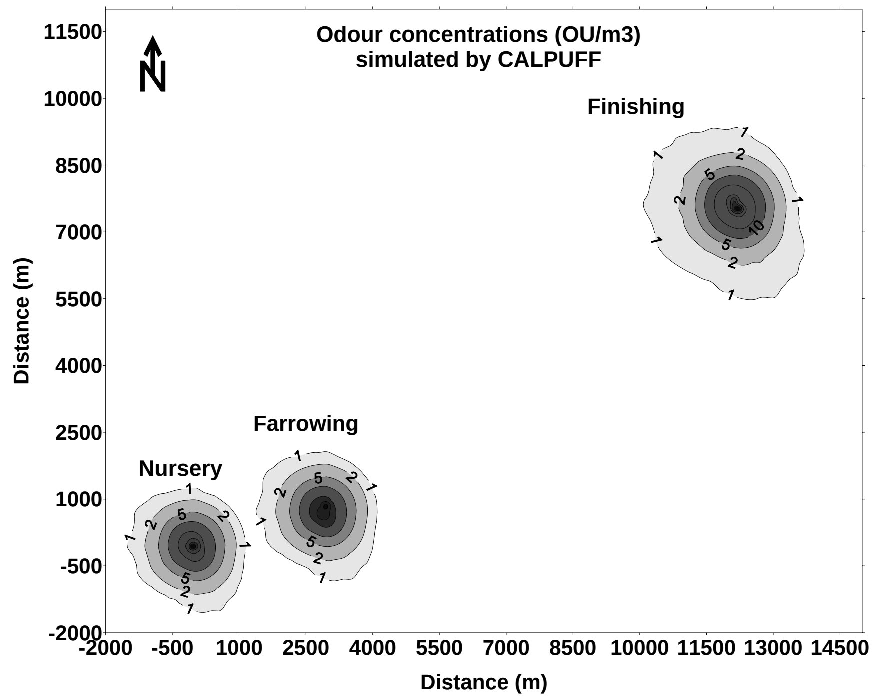


Figure 7.2 5-year average warm season odour concentration contour map of the swine farm simulated by CALPUFF

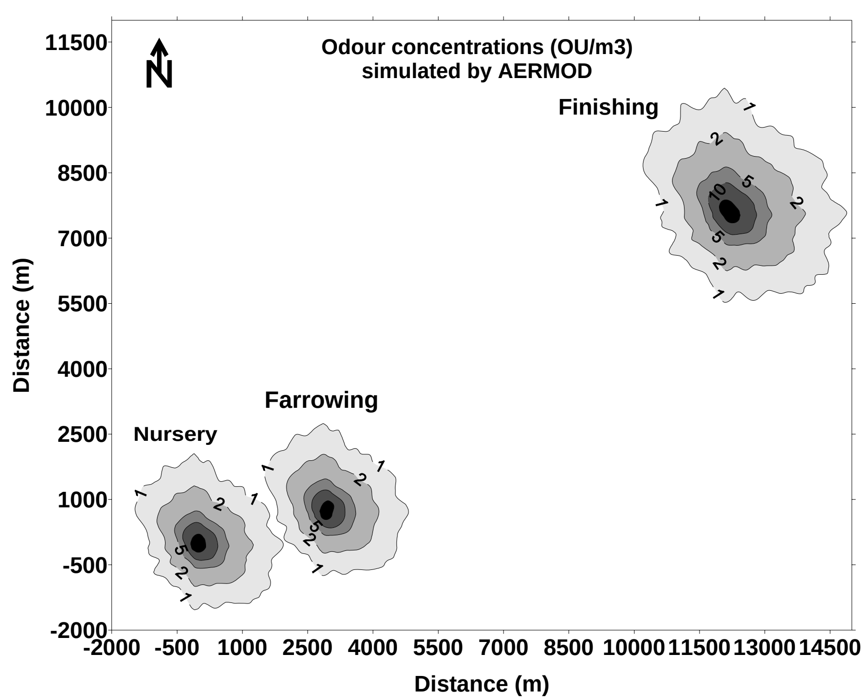


Figure 7.3 5-year average warm season odour concentration contour map of the swine farm simulated by AERMOD

Table 7.7 Maximum and minimum setback distances for different odour concentration values from Farrowing site in warm season as simulated by CALPUFF and AERMOD and recommended setback distances in three Prairie Provinces

Odour concentration level (OU/m^3)	Setback distance range predicted by two models (m)		Recommended minimum setbacks by Prairie Province odour guidelines (m)		
	CALPUFF	AERMOD	Saskatchewan	Alberta	Manitoba
1	1060 - 2570	850 - 3000	3200	1430	3600
2	920 - 1300	630 - 1500			
5	700 - 890	410 - 780			
10	500 - 650	300 - 450			

Table 7.8 Maximum and minimum setback distances for different odour concentration values from Nursery site in warm season as simulated by CALPUFF and AERMOD and recommended setback distances in three Prairie Provinces

Odour concentration level (OU/m^3)	Setback distance range predicted by two models (m)		Recommended minimum setbacks by Prairie Province odour guidelines (m)		
	CALPUFF	AERMOD	Saskatchewan	Alberta	Manitoba
1	1010 - 2440	850 - 3110	3200	1000	2000
2	870 - 1230	670 - 1510			
5	650 - 850	450 - 730			
10	450 - 600	320 - 450			

Table 7.9 Maximum and minimum setback distances for different odour concentration values from Finishing site in warm season as simulated by CALPUFF and AERMOD and recommended setback distances in three Prairie Provinces

Odour concentration level (OU/m^3)	Setback distance range predicted by two models (m)		Recommended minimum setbacks by Prairie Province odour guidelines (m)		
	CALPUFF	AERMOD	Saskatchewan	Alberta	Manitoba
1	1200 - 3040	1080 - 4000	3200	1270	2800
2	1050 - 1680	850 - 2200			
5	830 - 990	540 - 1100			
10	650 - 740	360 - 710			

7.5 Conclusions

1. Both of 5-year warn season average odour concentration contour maps simulated by CALPUFF and AERMOD in warm season showed odour traveled longer distance under prevailing wind directions;
2. 5-year warn season simulation results of AERMOD and CALPUFF fell in the same magnitude for each odour concentration level of 1, 2, 5 and 10 OU/m^3 for all three sites;
3. There were some differences between models predicted maximum odour setback distance and three Prairie Provinces, Canada odour control guidelines recommended odour MSD for both AERMOD and CALPUFF;
4. Scaling factor(s) as described in the evaluation of models in chapters 5 and 6 may be used in modeling; commonly used scaling factor(s) for a specific model, however, could not be available was the reason they were not used in this part;
5. MSD recommended by Prairie Provinces for odour control purpose only provided a certain distance; however, maximum odour setback distance predicted by AERMOD and CALPUFF varied depending on predicted odour concentration values. Comparison between by Prairie Provinces recommended MSD with model predicted setback distance seemed to be awkward because they could not be compared directly;
6. Further studies in terms of scaling factor(s) for a certain model and acceptable odour criteria should be involved. Acceptable odour criteria may include odour concentration and the corresponding desired odour-free-frequency.

8. CONCLUSIONS AND RECOMMENDATIONS

Use of Air dispersion models to predict odour concentrations downwind livestock facilities was proved to be a practical approach to determine proper setback distance between odour sources and neighboring residents to minimize negative impact of odour nuisance. A lot of researchers have applied air dispersion models in agricultural odour dispersion simulation though these models were originally developed for simulating industrial air pollutions. Applicability of air dispersion models in predicting odour concentrations in the vicinity of odour sources should be evaluated and validated before them being applied in a real odour dispersion simulation. Evaluation and validation of air dispersion models were conducted through comparing models predictions with field odour measurements. Field odour data were only accessible recently because of a large amount of work done by researchers and trained odour sniffers or resident-odour-observers related to those odour issue projects. AERMOD and CALPUFF were two air dispersion models selected to applied in this project because CALPUFF showed good performance in odour dispersion simulation proved by many other researchers and AERMOD was U.S. EPA newly recommended regulatory models and limited information of performance of AERMOD in odour dispersion simulation could be found till now. Sensitivity analysis of these two air dispersion models to major climatic parameters was carried out in prior to evaluation of them. Application of AERMOD and CALPUFF in determining odour setback distance for a selected farm was also made based on the results that these two models performed close in the chapters of evaluation of them.

Sensitivity analysis of AERMOD and CALPUFF was conducted under both of steady-state and variable meteorological weather conditions in a chosen swine farm in Calmar. Aim of sensitivity analysis of these two models was to find out extent of change of five major climatic parameters, i.e., mixing height, ambient temperature, stability class, wind speed, and wind direction, on the impact of odour dispersion. Evaluation of these two models was carried out using field odour data and concentration-intensity conversion equation from University of Minnesota and

University of Alberta. Application of the two models was conducted using historical warm season (from May to October continuous in one year) meteorological data from year 1998 to 2002 and a selected farm in Yorkton, Saskatchewan.

8.1 Summary of Conclusions

Some primary conclusions could be drawn based on the results of sensitivity analysis, evaluation, and application of AERMOD and CALPUFF in odour dispersion simulation as following:

8.1.1 Sensitivity Analysis of Models to Major Climatic Parameters

1. Mixing height had no impact on odour dispersion for both models;
2. Although ambient temperature had very limited influence at both of two models, there was a trend with increase of temperature, the odour concentration within 5 km from the odour source increased as predicted two models. The reason may be that when temperature increased, more odour molecules moved into the odour transportation direction, causing higher odour concentration in horizontal direction;
3. Atmospheric ability class had great impact on odour dispersion for both models. It was also found CALPUFF was more sensitive to stability class compared with AERMOD;
4. Wind speed had huge influence at odour dispersion for both models. It was also observed AERMOD was more sensitive to wind speed compared with CALPUFF;
5. Wind direction had limited influence at odour dispersion for both models. It was also noticed effect of wind direction on odour concentration values was obvious at close distance to the odour source but diminished until disappeared at the distance of 5 km. Based on this result, wind direction should be carefully considered when the farm was close to residential area;

6. Variable meteorological data simulation result showed odour traveled longer distance under prevailing wind directions. Difference of maximum odour travel distance between two models (with AERMOD predictions as the basis) was -6.1, 6, 30, 33.3, and 48.9% for odour concentration of 1, 2, 5, 10 and 20 OU/m^3, respectively. Different methods used to deal with calm weather condition and theories used to describe the movement of odour plume in atmosphere may be the two reasons caused the discrimination of models predictions.
7. Appropriate odour setback distance should be wind direction dependent, i.e., setback distance should be longer under prevailing wind directions and shorter under other directions. Both steady-state and variable meteorological data could be employed to predict odour setback distance; however, acceptable odour concentration should be based on the climatic parameters chosen under steady-state weather conditions.

8.1.2 Evaluation of AERMOD and CALPUFF in Odour Dispersion Simulation

Using Minnesota field odour plume data

1. Using conversion equation from University of Minnesota, the overall agreement of all field odour measurements and model predictions was 34.7 and 38.3% for AERMOD and CALPUFF, respectively; however, the overall agreement for field measured odour intensities without intensity and model predictions 0 was 17.6 and 20.7% for AERMOD and CALPUFF, respectively;
2. Using conversion equation from University of Alberta, the overall agreement of all field odour measurements and model predictions was 34.2 and 31.1% for AERMOD and CALPUFF, respectively; however, the overall agreement for field measured odour intensities without intensity 0 was 27.5 and 25.9% for AERMOD and CALPUFF, respectively;

3. Scaling factors can improve the agreement of model predictions and all field odour measurements by 14.8 and 10.7%, and model predictions and field odour measurements without intensity 0 by 10.1 and 9.4% for AERMOD and CALPUFF respectively, if conversion equation from University of Minnesota was applied;
4. It is better to choose conversion equation from University of Minnesota not that from University of Alberta for Minnesota odour plume data considering statistical evaluation results of model performance;

Using Alberta field odour plume data

5. Using conversion equation from University of Alberta, the overall agreement of all field odour measurements and model predictions was 24.0 and 23.3% for AERMOD and CALPUFF, respectively; however, the overall agreement for field measured odour intensities without intensity 0 and model predictions was 11.7 and 12.1% for AERMOD and CALPUFF, respectively;
6. Using conversion equation from University of Minnesota, the overall agreement of all field odour measurements and model predictions was 22.5 and 21.3% for AERMOD and CALPUFF, respectively; however, the overall agreement for field measured odour intensities without intensity 0 and model predictions was 12.1 and 11.3% for AERMOD and CALPUFF, respectively;
7. Scaling factors can improve the agreement of model predictions and all field odour measurements by 7.1 and 7.4%, and model predictions and field odour measurements without intensity 0 by 10.4 and 9.1% for AERMOD and CALPUFF respectively, if conversion equation from University of Minnesota was applied;
8. It is better to choose conversion equation from University of Alberta not that from University of Minnesota for Alberta odour plume data considering statistical evaluation results of model performance;

9. Inaccuracy of field measured odour plume data may be a key reason caused the low agreement of field odour measurements and models predictions for the odour plume data from both University of Minnesota and University of Alberta.

8.1.3 Application of AERMOD and CALPUFF in Determining Odour Setback Distance

1. 5-year warn season (May to October from 1998 to 2002) simulation results of AERMOD and CALPUFF for odour concentration levels of 1, 2, 5 and 10 OU/m^3 showed odour traveled longer distance under prevailing wind directions;
2. Differences existed between models simulated maximum odour setback distance and Canadian Prairie Provinces odour control guidelines recommended minimum separation distance for both AERMOD and CALPUFF;
3. Acceptable odour criteria may include odour concentration and the corresponding desired odour-free-frequency.

8.2 Recommendations for Future Studies

Future studies of air dispersion modeling in agricultural odour dispersion simulation could find ways in a model created for agricultural odour dispersion purpose, accurate measurement of field odour data, and acceptable odour criteria:

1. The currently used air dispersion models are originally created for industrial gases pollution simulation purpose. Experiments have proved a lot of differences exist between industrial

gases and agricultural odours. Development of a model for agricultural odour dispersion purpose may improve agreement of modeled and field measured odour occurrences;

2. Field measured odour data was obtained by trained odour sniffers or resident-odour-observers. These data may be not accurate due to some human-caused or external incidents. Two approaches could be provided to solve this problem: employing people who can detect odour intensities more objectively or using odour detecting machines to record the odour occurrences;
3. Widely acceptable odour criteria have not been set up by researchers till now. Acceptable odour criteria may conclude odour concentration that can be accepted by most of the normal people as well as odour occurrence frequency corresponding to a certain odour concentration value.

REFERENCES

Alberta Standards and Administration Regulation. 2000. Manure Nutrient Management, Irrigation Branch, Alberta Agriculture, Food and Rural Development (AAFRD), Edmonton, AB, CA. P 4.

Allen, R. G., R. Trezza, and M. Tasumi. 2006. Analytical integrated functions for daily solar radiation on slopes. Science Direct. Agricultural and Forest Meteorology 139 (2006) 55-73.

Allwine, K. J., W. F. Dabberdt and L. L. Simmons. 1998. PEER REVIEW OF THE CALMET/CALPUFF MODELING SYSTEM. The KEVRIC Company Inc. Durham, NC.

AMEC Earth & Environmental. 2003. First Interim Report, Literature Review and Model Selection, Odour Modeling for CFOs. Prepared for Alberta Agriculture, Food and Rural Development. Edmonton, Alberta.

Arya, S. 1999. Air pollution meteorology and dispersion. Oxford University Press, New York.

ASAE (American Society of Agricultural Engineers). 1994. EP379.1. Control of Manure Odors. ASAE standards. 41st ed. St. Joseph, MI: ASAE. P 546-547

ASTM. 1988. Standards practices for Referencing Suprathreshold Odor Intensity. E544-75. American Society for Testing and Materials, Philadelphia, PA.

Carney, P. G. and V. A. Dodd. 1989. A comparison between predicted and measured values for the dispersion of malodours from slurry. *Journal of agricultural Engineering Research.* 44(1): P 67–76.

CEN. 1999. Air quality-Determination of odour concentration by dynamic olfactometry. Draft prEN 13725. European committee for Standardization (CEN) Central Secretariat: rue de Stassart, 36 B-1050 Brussels.

Chastain, J. P., and F. J. Wolak. 1999. Application of a Gaussian plume model of odor dispersion to select a site for livestock facilities. Department of Agricultural and Biological Engineering, Clemson, S. C.: Clemson University.

Chen, Y., D. S. Bundy, and S. Hoff. 1998. Development of a model of dispersion parameters for odour transmission from agricultural sources. *Journal of agricultural Engineering Research* 69(3): P 229-238.

Cosemans, G. K., J. Janssen, and G. J. Maes. 1995: The third workshop's environmental impact assessment model intercomparison exercise. *International Journal of Environment and Pollution*, 5, 4-6, P 785-798.

Curran, T. P., A. D. Vincent, and L. M. William. 2007. Evaluation of ISC3 and CALPUFF Atmospheric Dispersion Models for Odour Nuisance Prediction. Presentation paper at the 2007 ASABE Annual International Meeting, Minneapolis, MI, U.S. Paper No: 074181.

Diosey, P. G., E. H. Maureen, and J. P. Richard. 2000. Modeling odour and VOCs: a comparison of models and modeling techniques. Water Environment Federation Specialty Conference: Odours and VOC Emissions 2000, Cincinnati, OH. 16-18 April 2000.

Feddes, J. J. R. and J. C. Segura. 2005. Relationship Between Odour Intensity and Concentration of n-Butanol, CSBE, Winnipeg, MN, Paper No. 05-020.

Ferenczi, Z. 2005. Sensitivity Analysis of the Mesoscale Puff Model – RIMPFF. Proceedings of the 10th International Conference on Harmonisation with Atmospheric Dispersion Modeling for Regulatory Purpose.

Fraser, H. W. 2001. Agricultural odours: 25 years of reducing complaints about barns and manure storages using the minimum distance separation formulae. *Journal of Water Science and Technology.* Vol. 44 (9): 211-217

Fritz, B. K., B. W. Shaw, and C. B. Parnell. 2005. Influence of meteorological time frame and variation on horizontal dispersion coefficients in Gaussian dispersion models. *Transactions of the ASAE.* Vol. 48(3): 1185-1196.

Guo, H., L. D. Jacobson, D. R. Schmidt, and R. E. Nicolai. 2001a. Calibrating Inpuff-2 model by resident-panelists for long-distance odour dispersion from animal production sites. *Applied Engineering in Agriculture.* Vol. 17(6): 859–868.

Guo, H., L. D. Jacobson, D. R. Schmidt, and K. A. Janni. 2001b. Simulation of Odour Dispersions As Impacted by Weather Conditions. Livestock Environment VI. P 687-695

Guo, H., L. D. Jacobson, D. R. Schmidt, and R. E. Nicolai. 2003. Evaluation of the Influence of Atmospheric Conditions on Odour Dispersion from Animal Production Sites. *Transactions of the ASAE*. Vol. 46(2): 461-466

Guo, H., L. D. Jacobson, D. R. Schmidt, R. E. Nicolai, J. Zhu, and K. A. Janni. 2004a. Development of the OFFSET Model for Determination of Odour-annoyance-free Setback Distances from Animal Production Sites: Part II. Model Development and Evaluations. *Transactions of the ASAE*. Vol. 48(6): 2269-2276

Guo, H., L. D. Jacobson, D. R. Schmidt, R. E. Nicolai, and K. A. Janni. 2004b. Comparison of five models for setback distance determination from livestock sites. *Canada Biosystems Engineering*. Vol. 46. 617-625.

Guo, H., L. D. Jacobson, D. R. Schmidt, R. E. Nicolai, J. Zhu, and K. A. Janni. 2005a. Development of the OFFSET model for determination of Odour-annoyance-free setback distance from animal production sites, Part II: Model development and evaluations. *Transactions of ASAE.* Vol. 48(6): 2269-2276.

Guo, H., W. Dihod, J. R. Feddes, C. Lague, and I. Edeogu. 2005b. Monitoring odour occurrence in the vicinity of swine farms by resident observers – Part I: Odour occurrence profiles. *Canada Biosystems Engineering*. Vol. 47(6): 57-6.65.

Guo, H., W. Dehod, J. Agnew, J. R. Feddes, and S. Pang. 2006. Annual Odour Emission Rate from Different Types of Swine Production Buildings. *Transactions of the ASABE*. Vol. 4(2): 517-525

Harssema, H. 1991. Field measurement of odourous air pollution with panels. In *Odour and Ammonia Emissions from Livestock Farming*, Eds. V. C. Nielsen, J. h. Voorbug and P. L. Hermite, 203-211, Elsevier Applied Science, New York.

Henry, C. G., P. C. D. Alreton, R. J. Ormerod, G. G. Galvin, S. J. Hoff, L. D. Jacobsen, D. D. Schulte, and D. L. Billesbach. 2007. Downwind Odour Predictions from Four Swine Finishing Barns Using CALPUFF. International Symposium on Air Quality and Waste Management for Agriculture. CD-Rom Proceedings of the 16-19 September 2007 Conference.

Jacobson, L. D., K. A. Janni, and L. J. Johnston. 1998. Odor and gas reduction from sprinkling soybean oil in a pig nursery. ASAE Paper No. 98–4125. St. Joseph, Mich: ASAE.

Jacobson, L. D., H. Guo, D. R. Schmidt, R. E. Nicolai, J. Zhu, and K. Janni. 1999. Worksheet for odor rating system to estimate setback distances from animal production sites. Released October 1999.

Jacobson, L. D., H. Guo, D. R. Schmidt, and R.E. Nicolai. 2000. Calibrating an odor dispersion model by resident-panelists. Second International Conference on Air Pollution from Agricultural Operations (held by ASAE). Des Moines, Iowa, October 9-11, 2000.

Jacobson, L. D., L. W. Susan, D. R. Schmidt, A. J. Heber, J. R. Bicudo, and R. R. D. Moon. 2002. Site Selection of Animal Operations Using Air Quality Criteria. National Center for Mannure and Animal Waste Management, North Carolina State University, Raleigh, N.C. P 3

Jacobson, L. D., H. Guo, D. R. Schmidt, R. E. Nicolai, J. Zhu, and K. A. Janni. 2005. Development of the OFFSET Model for Determination of Odor-annoyance-free Setback Distances from Animal Production Sites: Part I. Review and Experiment. 2005. ASAE Annual Meeting. Paper No: 004044.

Jacques Whitford Environment Limited. 2003. Standard practice document for use of the dispersion factor in the calculation of minimum distance separation in the agricultural operation practices act. Project No.: ABC20286. Calgary, Alberta, Canada: Jacques Whitford Environment Limited.

Janni, K. A. 1982. Modeling dispersion of odourous gases from agricultural sources. *Transactions of ASAE.* Vol. 25(6): 1721-1723.

Jones, M. 1992. Odour Measurement Using Dynamic Olfactometry. In: Odour Update 92: Proceedings of a workshop on Agricultural Odours. MRC Report No. DAQ 64/24, Department of Primary Industries, Toowoomba, QLD. April. P 17-32.

Kelly, J. P. 1995. Ammonia and Odour emissions from Agricultural Sources: A Review. Factory of Engineering and Surveying, University of Southern Queensland, Toowoomba, Queensland, Australia. P 57.

Koppolu, L., D. D. Schulte, S. Lin, M. J. Rinkol, D. P. Billesbach, and S. B. Verma. 2002. Comparison of AERMOD and STINK for Dispersion Modeling of Odourous Compounds. Presentation paper at 2002 ASAE Annual International Meeting, Chicago, Illinois, U.S. Paper No: 024015

Koppolu, L., D. D. Schulte, and L. D. Jacobson. 2004. Development of scaling factors (peak-to-mean ratios) through dispersion modeling with AERMOD and field-based odour measurements for livestock facilities. ASAE paper No: 044196. ASAE, St. Joseph, MI.

Li, Y., and H. Guo. 2006. Evaluating the Impact of Computational Time Interval on Livestock Odour Dispersion Using a Computation Fluid Dynamics Model. An ASAE Meeting Presentation. Paper No: 06173.

Lim, T. T., A. J. Heber, J. Q. Ni, R. Grant, and A. Sutton. 2000. Odour impact distance guideline for swine production systems, Odour and VOC emissions 2000 Conference Proceedings, Water Environment Federation. Hyatt Regency, Cincinnati, Ohio. April. P 16-19.

Manitoba Agricultural Guidelines Development Committee. 2007. Farm Practices Guidelines for Pig Producers in Manitoba. Manitoba Agriculture, Food and Rural Initiatives.

McGinley, C. M., M. A. McGinley, and D. L. McGinley. 2002. “Odour basics”: Understanding and using odour testing. In Proceedings of 22nd Annual Hawaii Water Environment Association Conference. Honolulu, Hi. 6–7 June. Honolulu, Hi.: Hawaii Water Environment Association.

McHugh, C. A., D. J. Higson, and S. J. Dyster. 1999. Comparison of model evaluation methodologies with application to ADMS 3 and US model. Cambridge Environmental Research Consultants, 3 Kings Parade, Cambridge, UK.

Mejer, G. J. and K. H. Krause. 1985. Dispersion models for emissions from agricultural sources. In Odour prevention and Control of Organic Sludge and Livestock farming, eds. V.C. nielson, J. H. voorburg, P.L. herminte. London: Elsevier.

Miner, J. R. and C. L. Barth. 1988. Controlling Odours from Swine Buildings, PIH-33. Pork Industry Handbook, Purdue University Cooperative Extension Service, West Lafayette, IN.

New Zealand National Institute of Water and Atmospheric Research, Aurora Pacific Limited, and Earth Tech. 2004. Good Practice Guide for Atmospheric Dispersion Modelling. Published by the Ministry for the Environment, PO Box 10-362, Wellington, New Zealand.

NCMAWM. 2001. White Papers - Odor Mitigation for Concentrated Animal Feeding Operations: White Paper and Recommendations. MWPS, Iowa State University, Ames, IA.

Olesen, H. R. 1998, 'Model Validation Kit - Status and Outlook'. Presented at the 5th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purpose in Rhodes, May 1998.

Olesen, H. R. 1999. Model Validation Kit-Recent Development. Rouen, 11-14 October 1999. National Environmental Research Institute, Denmark.

OMAFRA (Ontario Ministry of Agriculture, Food, and Rural Affairs). 1995. Minimum distance separation I and Π.

Ormerod, R. J. 1991. Modeling emissions and dispersion of feedlot odour: a case study. Proceedings of a workshop on agricultural odours. Toowoomba, Queensland, Australia.

Ouellette, C. A., J. C. Segura, and J. J. R. Feddes. 2006. Persistence: Odour Intensity and Concentration Relationship for Livestock Odours Presentation paper at the CSBE/SCGAB 2006 Annual Conference. Paper No. 06-146.

Ould-Dada, Z. 2008. Reliability Of Atmospheric Dispersion Models Used In Assessing The Impact Of Radioactive Discharges On Food Safety. Food Standards Agency Radiological

Protection and Research Management Division Room 715B, Aviation House, 125 Kingsway London WC2B 6NH, United Kingdom.

Pasquill, F. 1961. The estimation of the dispersion of wind-borne material. The meteorological Magazine, UK Met. Office 1961: P 34-49.

Qu, G., D. Scott, J. C. Segura, and J. J. R. Feddes. 2006. Calibration of the ISC-PRIME Model for Odour Dispersion. Presentation paper at 2006 ASABE Annual International Meeting. Portland, Oregon. Paper No: 064136.

Saskatchewan Agriculture and Food. 1999. Guidelines for Establishing and Managing Livestock Operation. 3M ISBN 0-88656-682-7 LOG 04/99R: 5.

Schmidt, D. R. and L. D. Jacobson. 2006. Hydrogen Sulfide Dispersion, Summary of Model Farms. Presentation paper at the 2006 ASABE Annual International Meeting.

Schauberger, G. and M. Piringer. 1997. Assessment of the protection distance to avoid annoyance by odour sensation caused by livestock husbandry by the Austrian guideline. In Proc. International Symposium on Ammonia and Odour Control from Animal Production Facilities, Vol. 2: 677–684.

Schauberger, G., M. Piringer, and E. Petz. 2005. Sensitivity Analysis of Dispersion Models to Assess Odour Nuisance: A Qualitative Comparison with Complaint Statics.
Proceedings of 17th International Congress of Biometeorology. Sept 5-9, 2005, Garmisch-Partenkirchen

Scire, J. S., D. G. Strimaitis, and R. J. Yamartino. 2000. A user's guide for the CALPUFF dispersion model (version 5), Earth Tech, Inc., Concord, MA.

Segura J. C. and B. Morin. 2003. Protocols followed during the barn odour sampling and nasal ranging during the summer of 2003 at the Shooters Hill livestock farm site, Calmar, Alberta. University of Alberta and AAFRD, Edmonton, Alberta.

Smith, R. J. 1993. Dispersion of odours from ground level agricultural sources. *Journal of Agriculture Engineering Research*. Vol. 54(1993), P 187-200.

SRF Consulting Group, Inc. 2004. A Review of National and International Odour Policy, odour Measurement technology and Public Administration. SRF Consulting Group, Inc. One Carlson Parkway North, Suite 150 Minneapolis, MN 55447-4443. SRF No: 0034734.

Sweeten, J. M. 1998. Separation Distances for Swine Odor Control in Relation to Manure Nutrient Balances. *Applied Engineering in Agriculture*. Vol. 14(5): 543-549.

Sweeten, J. M., L. D. Jacobson, A. J. Heber, D. R. Schmidt, J. C. Lorimor, P. W. Westerman, J. R. Miner, R. H. Zhang, C. M. Williams, and B. W. Auvermann. 2001. Odor Mitigation for Concentrated Animal Feeding Operations: White Paper and Recommendations. National Center for Mannure and Animal Waste Management, North Carolina State University, Raleigh, N.C. P 19-28

Iowa Department of Natural Resources Animal Feeding Operations Technical Workgroup. 2004. Animal Feeding Operations Technical Workgroup Report on: Air Emissions Characterization, Dispersion Modeling, and Best Management Practices.

Thomas, P. C., V. A. Dodd, and L. M. William. 2007. Evaluation of ISC3 and CALPUFF Atmospheric Dispersion Models for Odour Nuisance Prediction. Prasentation paper at the 2007 ASABE Annual International Meeting.

Turner, D. B. 1970. Workbook of Atmospheric Dispersion Estimates (Revised). Ap-26. Office of Air Programs. U.S. Department of Health, Education, and Welfare, Research Triangle Park, NC.

USEPA. 1992. Protocol for Determining the Best Performing Model. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/R-92-025.

USEPA. 1998. A Comparison of CALPUFF with ISC3. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/R-98-020.

USEPA. 1999. State Compendium: Programs and Regulatory Activities Related to Animal Feeding Operations. U.S. Environmental Protection Agency, Research Triangle Park, NC.

USEPA. 2000. Meteorological Monitoring Guidance for Regulatory Modeling Applications. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/R-99-005.

USEPA. 2002. Compendium of Report from the Peer Review Process for AERMOD. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 2771.

USEPA. 2003. AERMOD: Latest Features and Evaluation Results. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/R-03-003.

USEPA. 2004a. User's Guide for the AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/B-03-002.

USEPA. 2004b. User's Guide for the AMS/EPA Regulatory Model – AERMOD. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-454/B-03-001.

USEPA. 2005. Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions. U.S. Environmental Protection Agency, Research Triangle Park, NC. 40 CFR Part 51.

US National Research Council. 1979. Odour from stationary and mobile sources. National Academy of Sciences, Washington, D.C. P 491.

Walker, J. I., M. Scaplen, and F. George. 2002. ISCST3, AERMOD and CALPUFF: A Comparative Analysis in the Environmental Assessment of a Sour Gas Plant. Jacques Whitford Environment Limited (JWEL) report paper. Paper No: 25.

Wang, L., C. B. Parnell, D. B. Parker, R. E. Lacey, and B. W. Shaw. 2005. Determination of Odour Emission Rates from Cattle Feedlots Using CALPUFF and ISCST3 Models. Presentation paper at 2005 ASAE Annual International Meeting.

Weil, J. C. 1992. Updating the ISC model through AERMIC. Preprints, 692 Journal of Applied Meteorological Volume 44 85th Annual Meeting of Air and Waste Management Association, Pittsburgh, PA, Air and Waste Management Association, Publication 92-100.11, P 14.

Williams, M. L. and N. Thompson. 1986. The effects of weather on odour dispersion from livestock buildings and from fields. In Odour prevention and control of organic sludge and livestock farming. Eds. Nielsen, J.H. Voorburg and P. L'Hermite. London. Elsevier Applied Science Publishers. P 227-233.

Xing, Y., H. Guo, J. Feddes, Z. Yu, S. Shewchuck, and B. Predicala. 2006. Sensitivity of Four Air Dispersion Models to Climatic Parameters for Swine Odour Dispersion. *Transactions of the ASABE*. Vol. 50(3): 1007−1017.

Xing, Y. 2007. Evaluation of Four Commercial air dispersion models for Livestock odour Dispersion Simulation. Thesis for Master degree. Department of Agricultural and Bioresouces Engineering, University of Saskatchewan, Saskatoon, SK. CA.

Zhang, Q., J. J. R. Feddes, I. K. Edeogu, and X. Zhou. 2002. Correlation between odour intensity assessed by human assessors and odour concentration measured with olfactometers. *Canadian Biosystems Engineering*. Vol. 44: 627-632

Zhang, Q., X. J. Zhou, H. Guo, and Y. Li. 2005. Odour and greenhouse gas emissions from hog operations. Final report. Winnipeg, Manitoba: Manitoba Livestock Manure Management Initiative, Inc.

Zhou, X., Q. Zhang, H. Guo, and Y. Li. 2005. Evaluation of air dispersion models for livestock odour application. Presentation paper at 2005 CSAE annual meeting. Winnipeg, MB. Paper No: 05-026.

Zhu, J., L. D. Jacobson, and D. Schmidt. 1998. Modeling the Agricultural Odor Dispersion Using Atmospheric Dispersion Models. Presentation paper at ASAE Meeting, Coronado Springs Resort Orlando, Florida, U.S. July 11-16. Paper No. 984056.

Zhu, J. 1999. The influence of stability class on downwind odor concentration predicted by air dispersion models. *Journal of Agricultural Engineering Reseach*. Vol. 34(10): 1919-1931.

Zhu, J., L. K. Jacobson, D. R. Schmidt, and R. Nicolai. 2000. Evaluation of INPUFF-2 model for predicting downwind odors from animal production facilities. *Applied Engineering in Agriculture.* Vol. 16(2): 159-164.

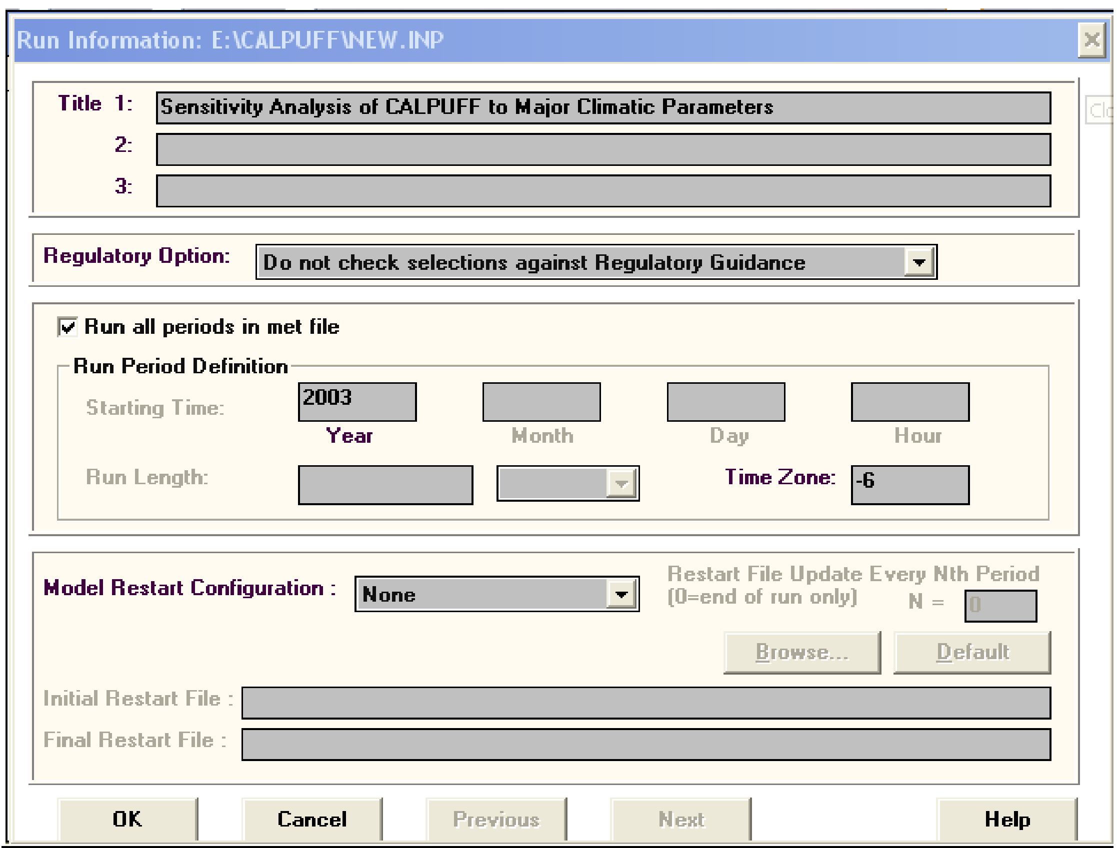
Zwicke, G. W. 1998. The dispersion modeling of particulate for point and multiple point sources in agriculture. MS thesis. Department of Biological and Agricultural Engineering, College Station, Texas: Texas A&M University.

APPENDICES

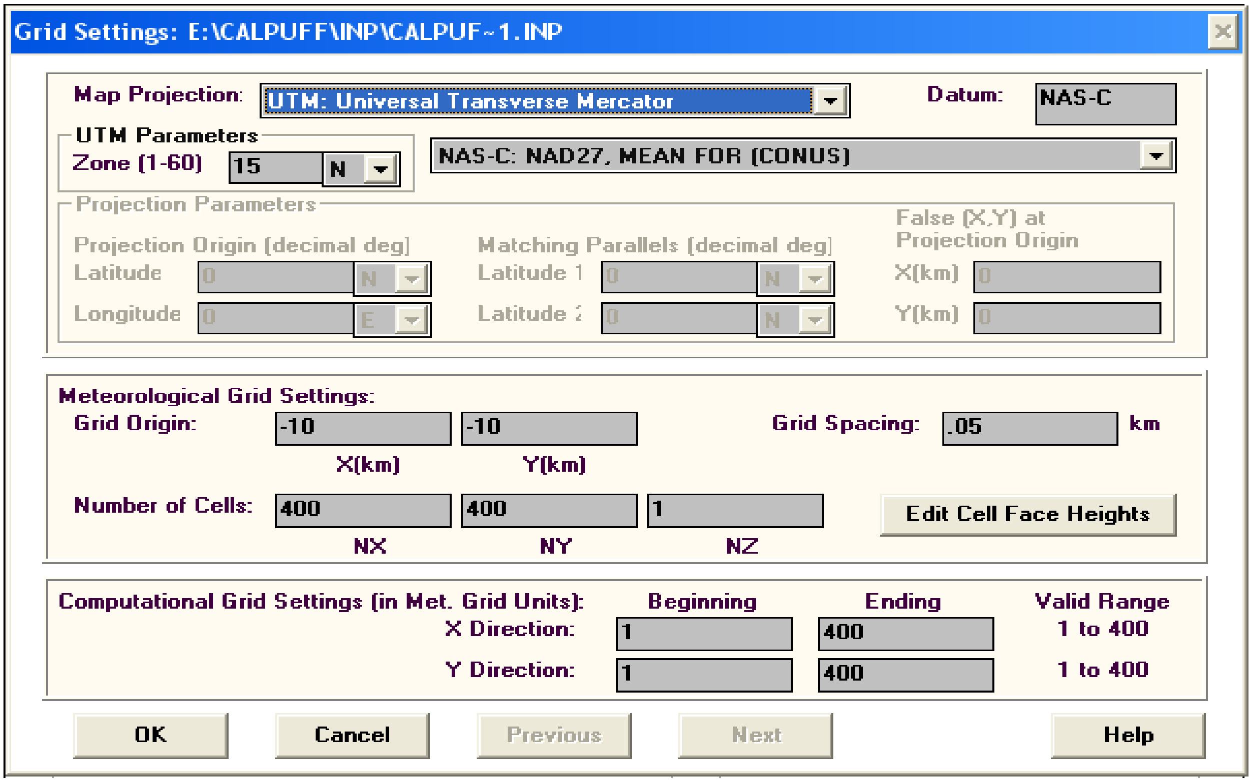
Appendix A: GUI run-stream screen of CALPUFF V5.7 (CALPUFF* and CALPOST)

Run-stream screen of graphical user interface of CALPUFF of version 5.7 as a step by step example in the part of model sensitivity analysis was shown below:

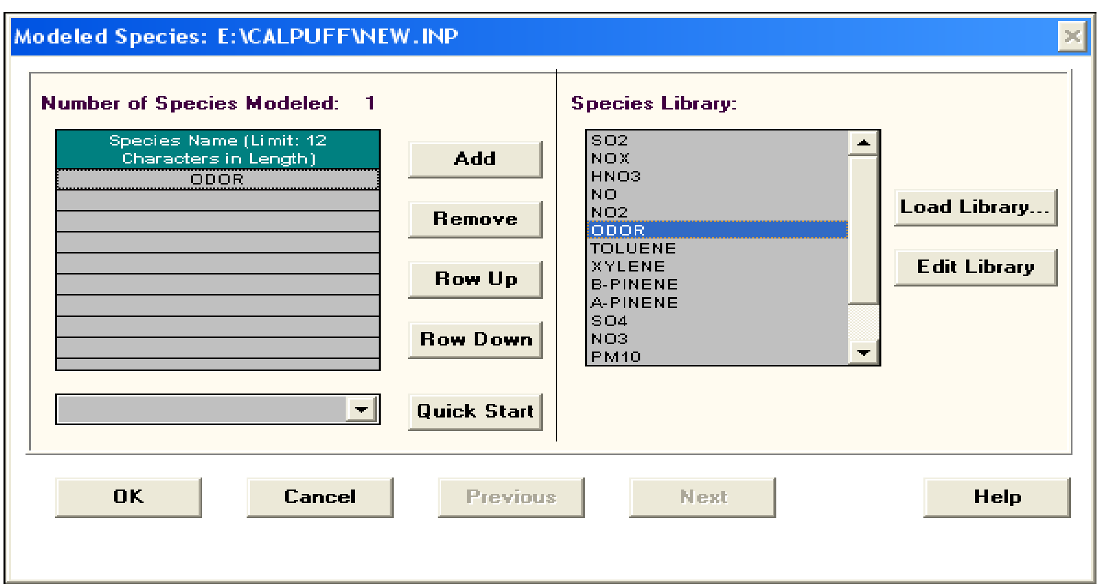
Screen 1: Run Information. Only one title was used "Sensitivity Analysis of CALPUFF to Major Climatic Parameters". Turn to the option "Do not check selections against Regulatory Guidance" because this application does not use a CALMET meteorological data and will not pass the regulatory guidance checks. Check the box to "run all periods in met file" and the provided the starting year of 2003, and the associated "Time Zone" is -6. "Model Restart Configuration" option is None;



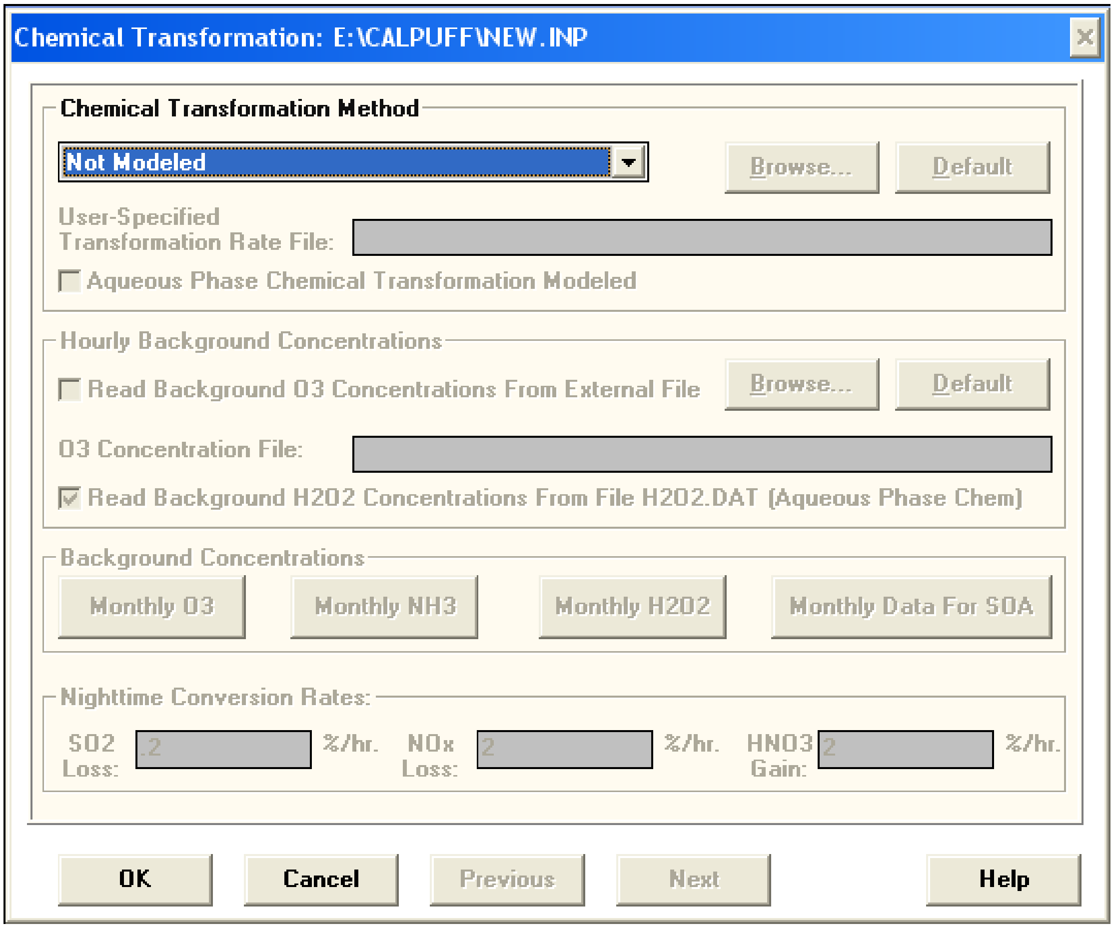
Screen 2: Grid Settings. In the "Map Projection" box, choose UTM: Universal Transverse Mercator and "UTM Zone" is 15, N, and NAS-C: NAD 27, MEAN FOR (CONUS). In the "Meteorological Grid Settings" boxes, "Grid Origin" is (-10, -10) for (X, Y) (km), and "Grid Spacing" is 0.05 km. "Number of Cells" is (400, 400, 1) for (NX, NY, XZ);



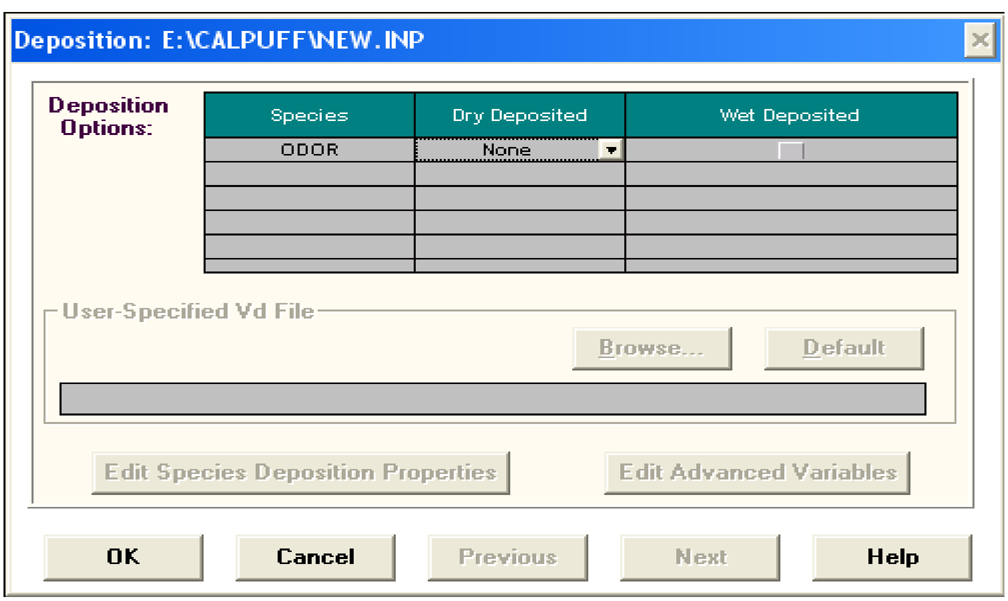
Screen 3: Modeled Species. ODOR is the only modeled species;



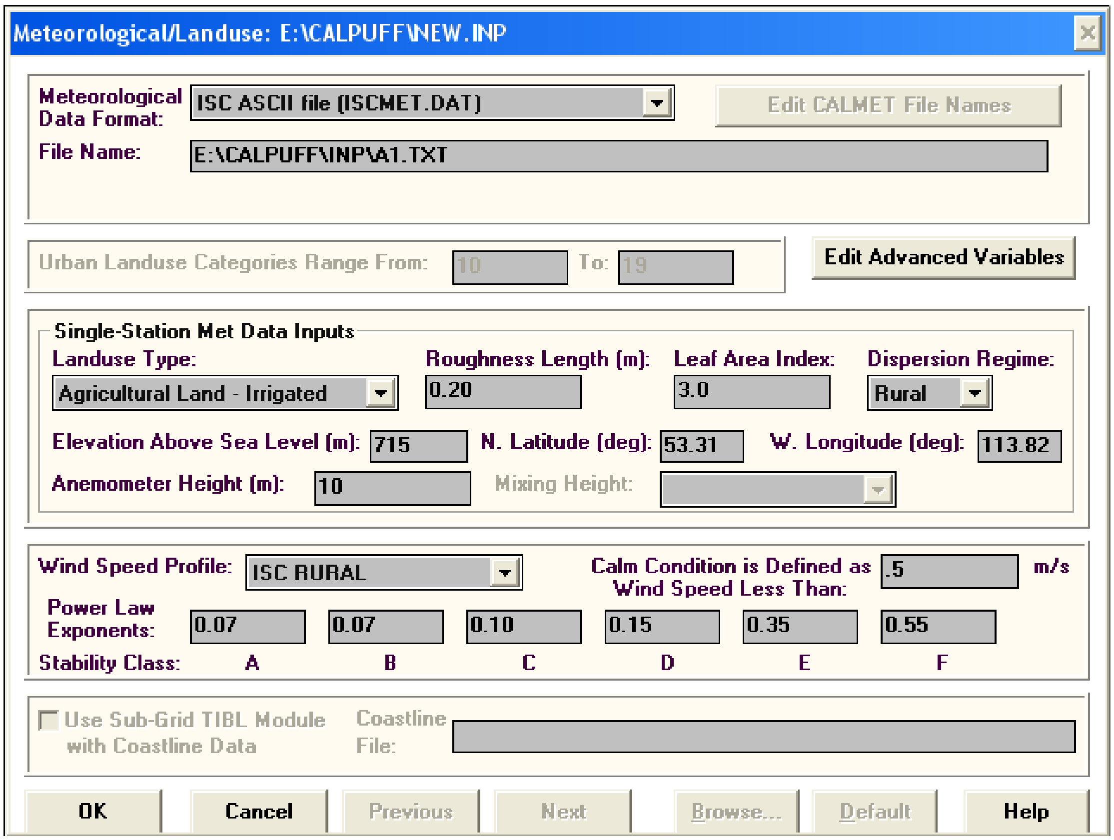
<u>Screen 4: Chemical Transformation</u>. No Chemical Transformation is used here



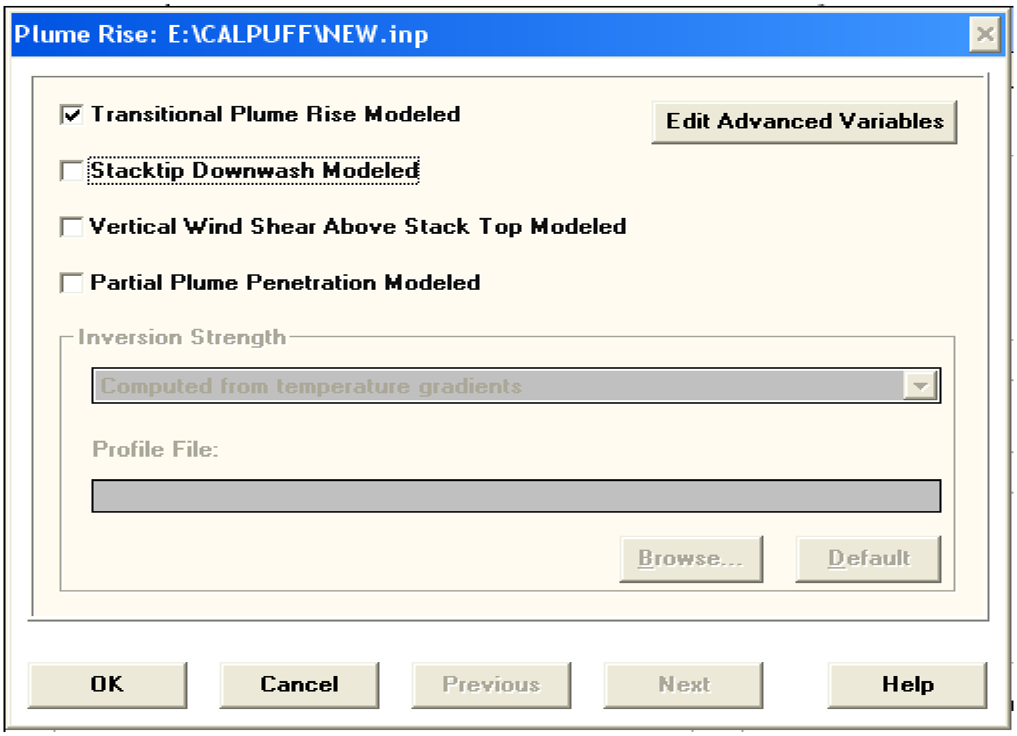
<u>Screen 5: Deposition</u>. Neither "Dry Deposition" nor "Wet Deposition" is considered;



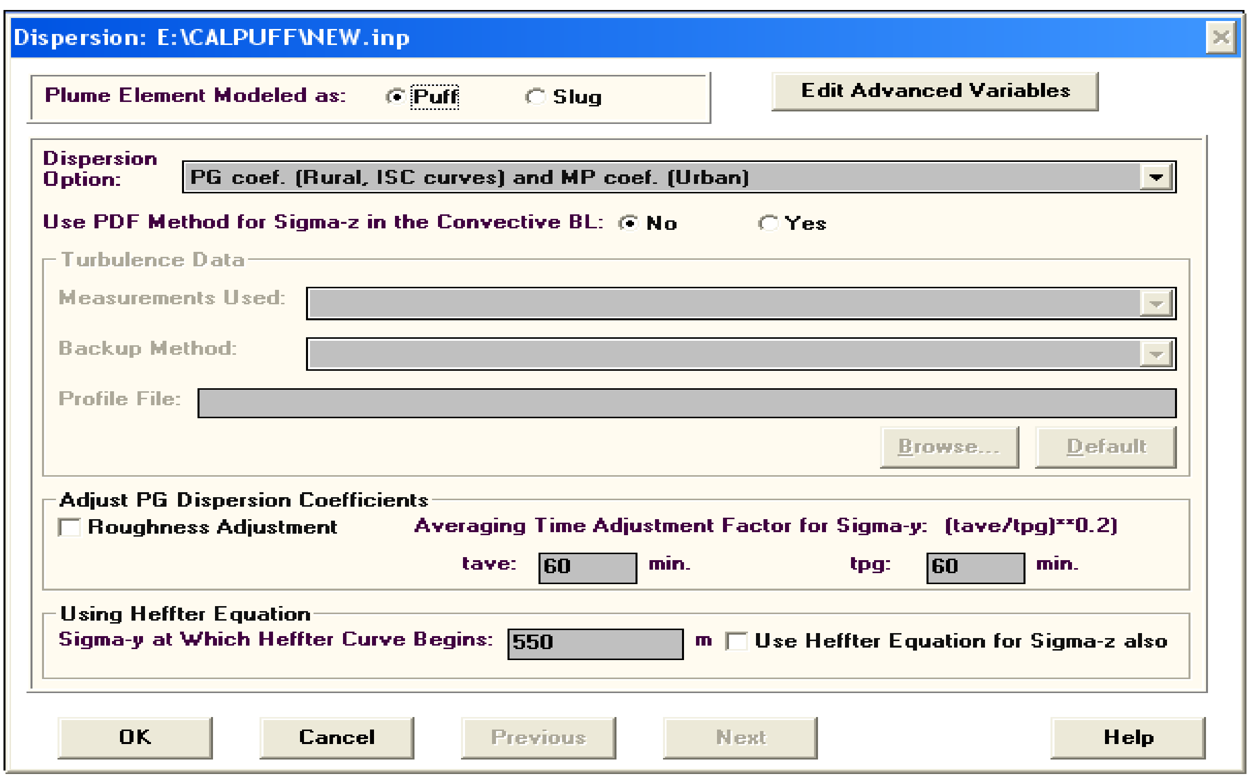
<u>Screen 6: Meteorological/Landuse</u>. In the "Meteorological Data Format" box, select ISC ASCII File and provide the file name in the box of "File Name". In the "Landuse Type" box, choose Agricultural Land – unirrigated, and a "Roughness Length" value of 0.20. "Dispersion Regime" is Rural. "Elevation Above Sea Level (m)" of the simulated area is 715. "Latitude" and "Longitude" of the area is 53.31N, 113.82W, respectivley. In "Wind Speed Profile" box choose ISC RURAL. Other defaults are retained;



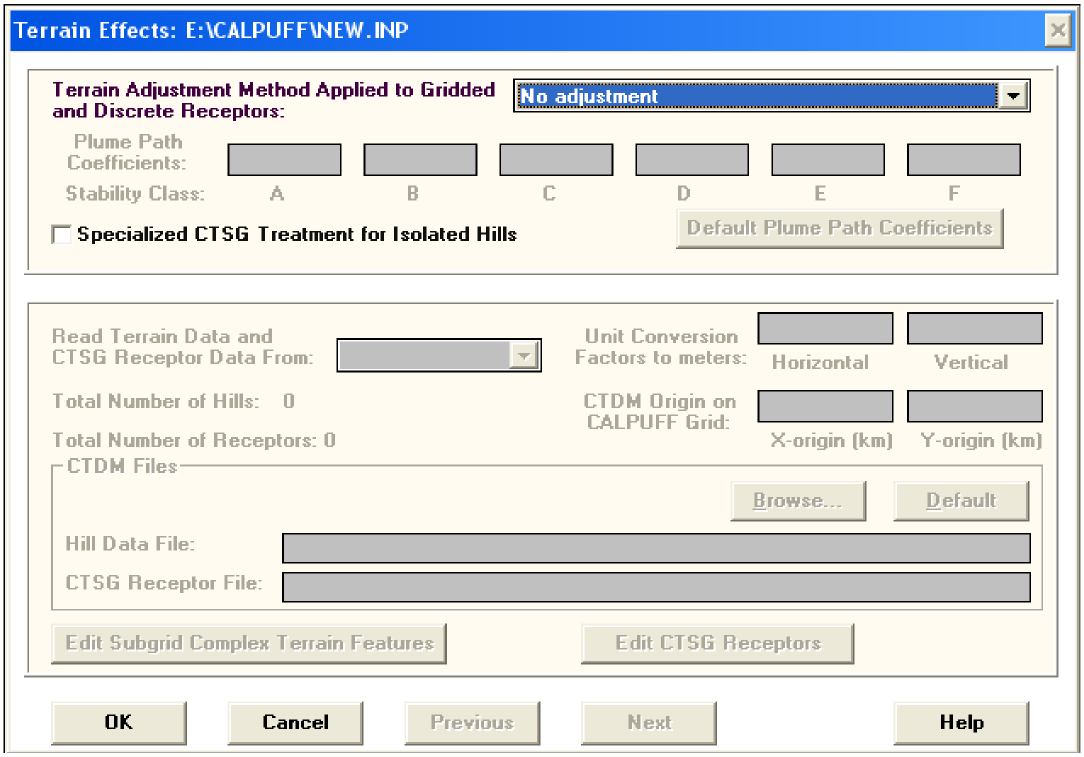
Screen 7: Plume Rise. Only "Transitional Plume Rise Modeled" is selected;



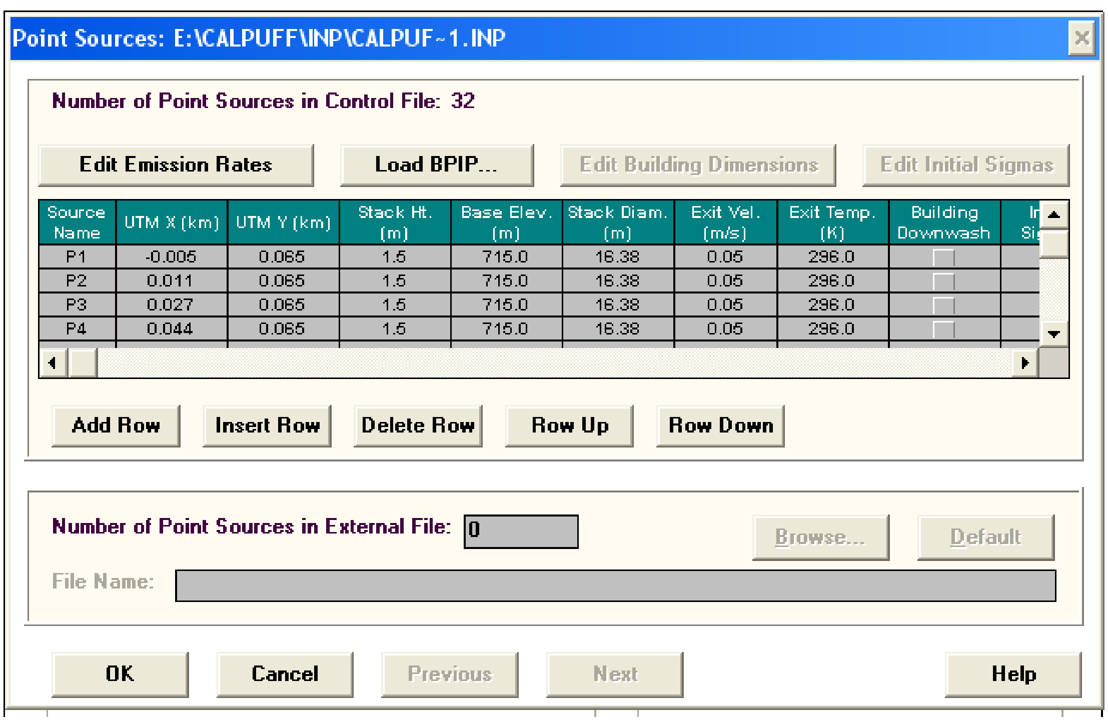
Screen 8: Dispersion. In "Plume Element Modeled", PUFF is selected. Retain all other default settings. Other defaults are retained;



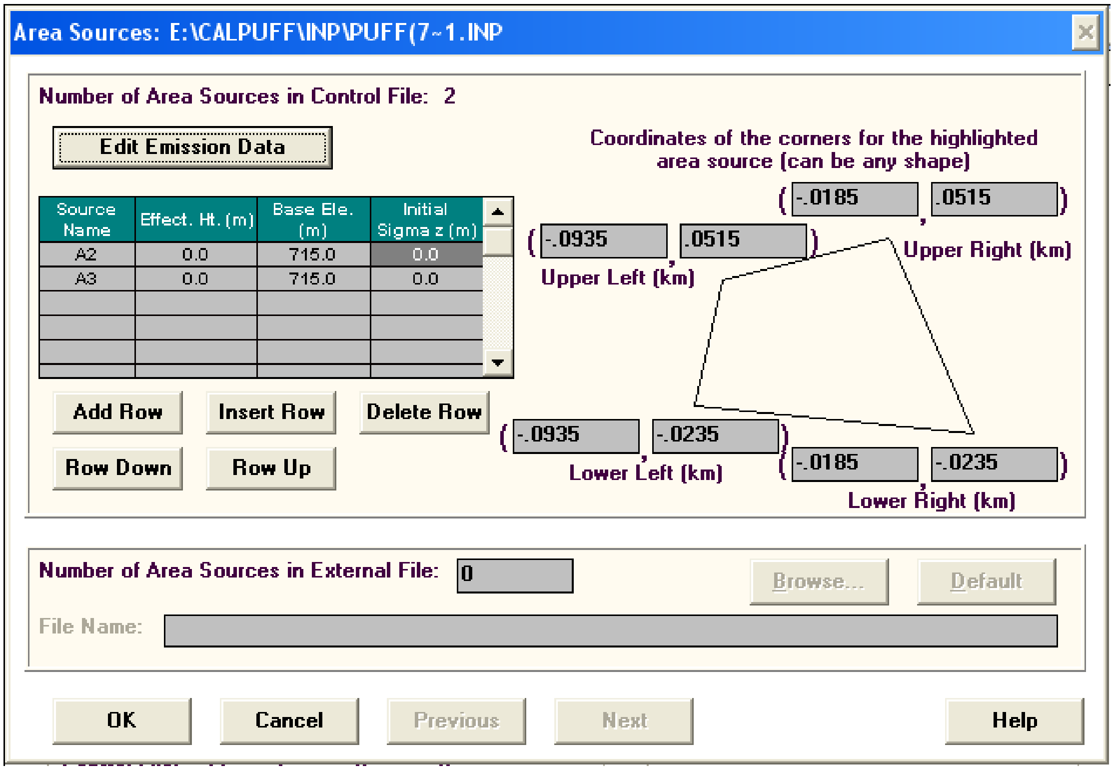
Screen 9: Terrain Effects. Choose No Adjustment in the box of "Terrain Adjustment Method Applied to Gridded and Discrete Receptors". Other defaults are retained.



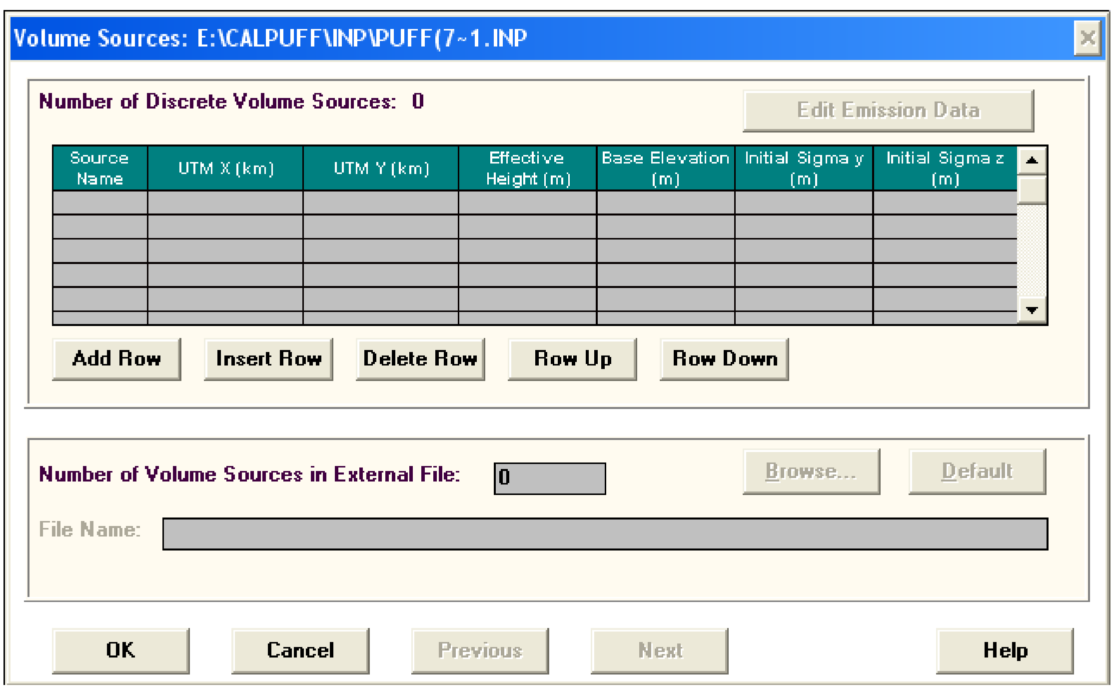
Screen 10: Point Sources. Detailed information of 32 point sources is provided on this screen;



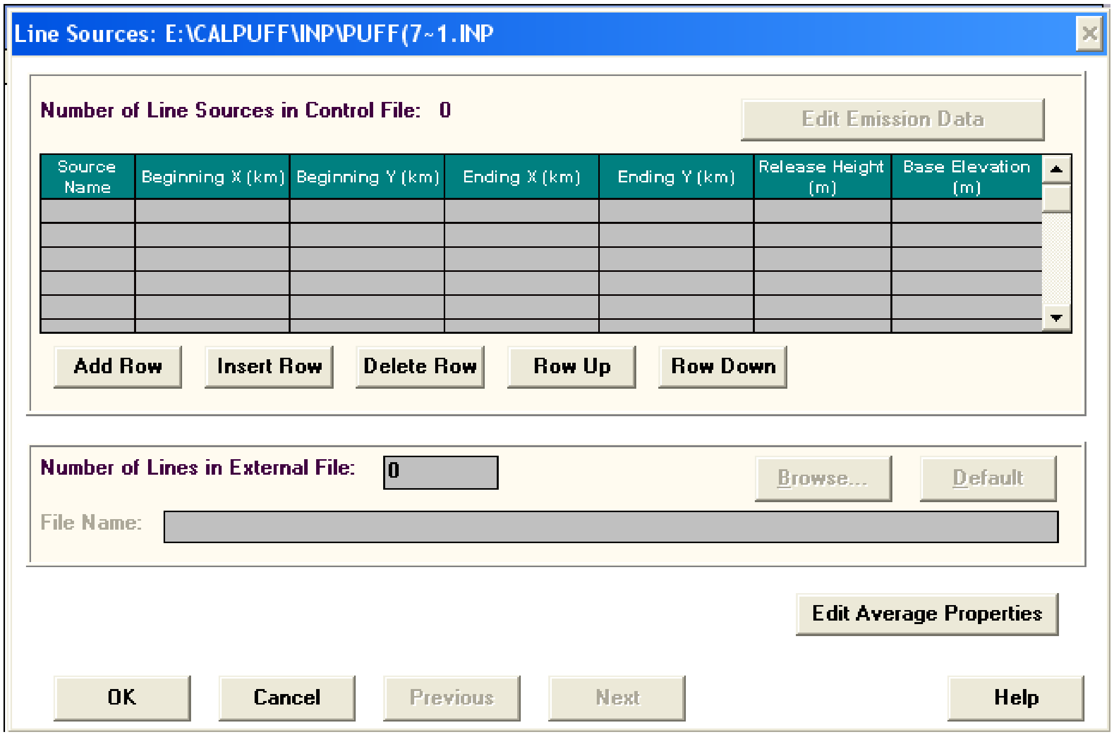
Screen 11: Area Sources. Detailed information of two area sources is provided on this screen;



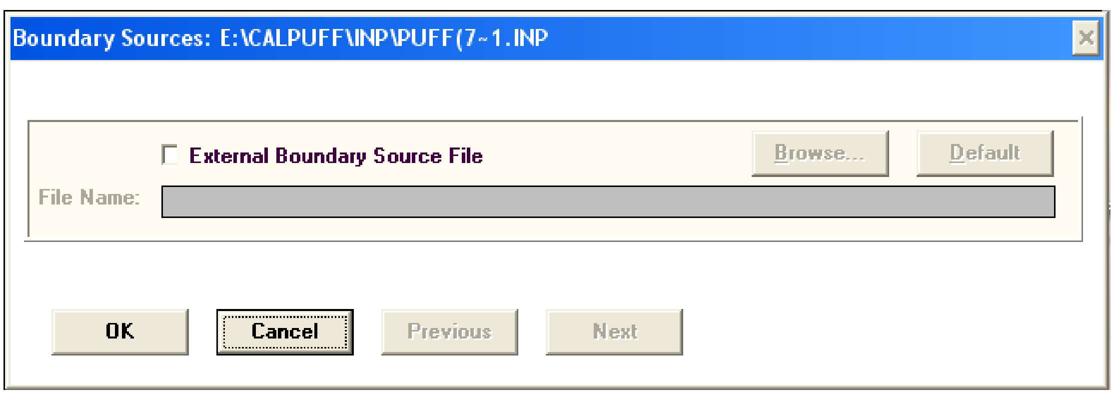
Screen 12: Volume Sources. No volume source is involved;



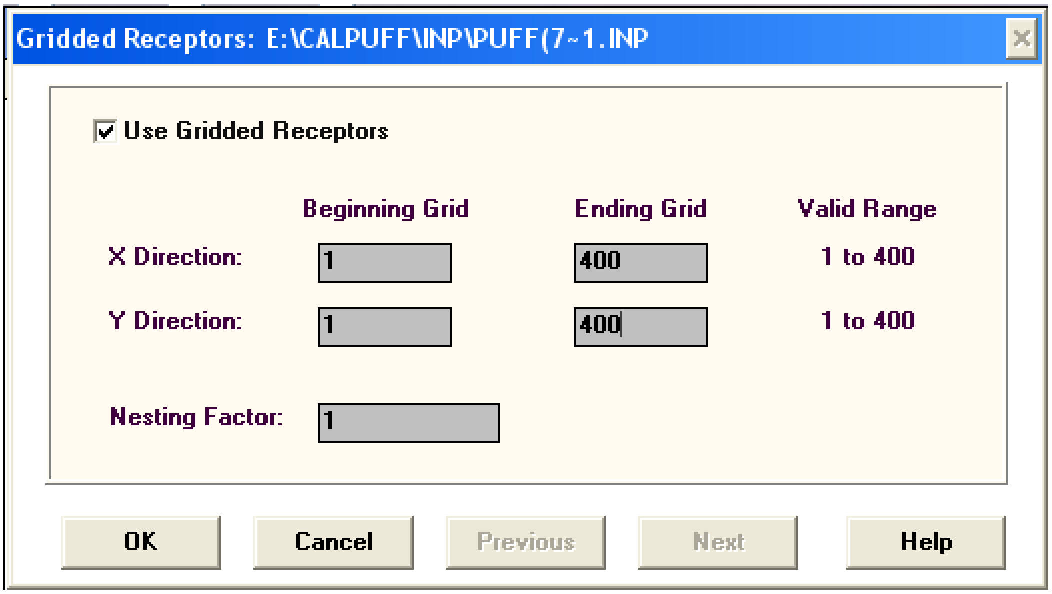
Screen 13: Buoyant Line Sources. No Buoyant Line Sources are involved;



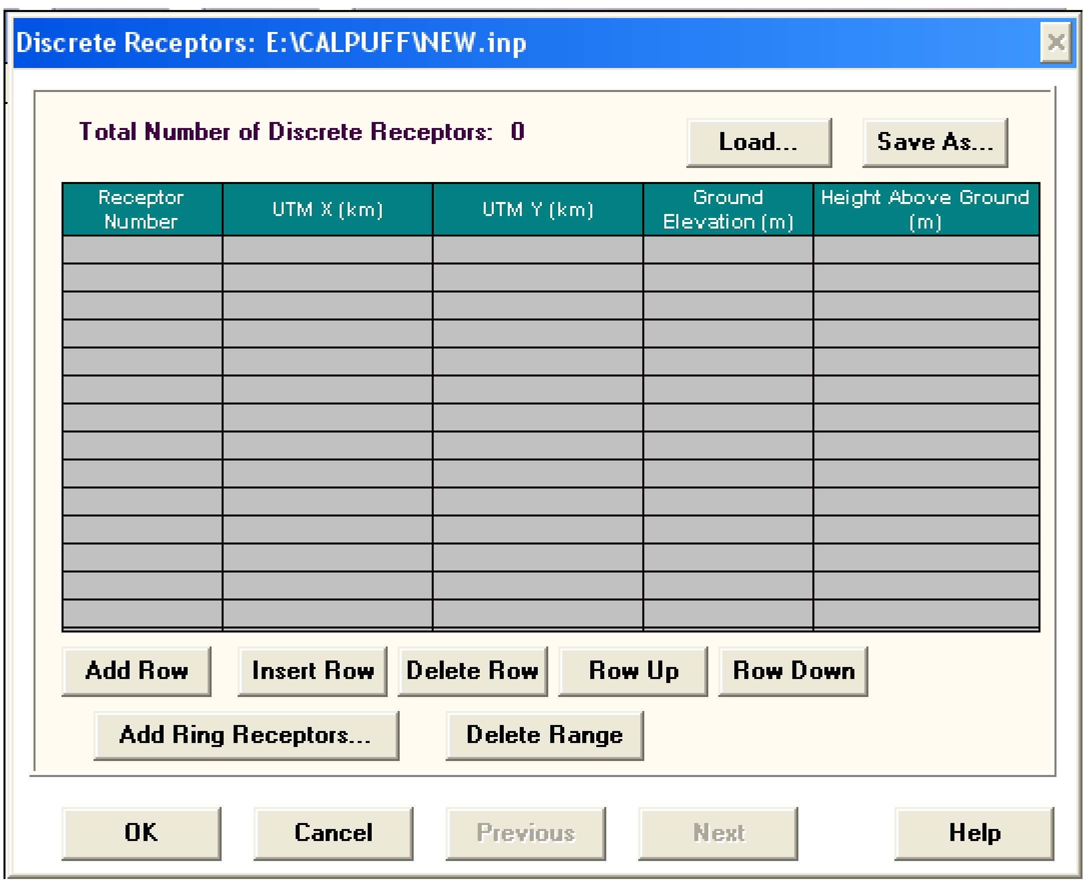
Screen 14: Boundary Sources. No boundary source is related;



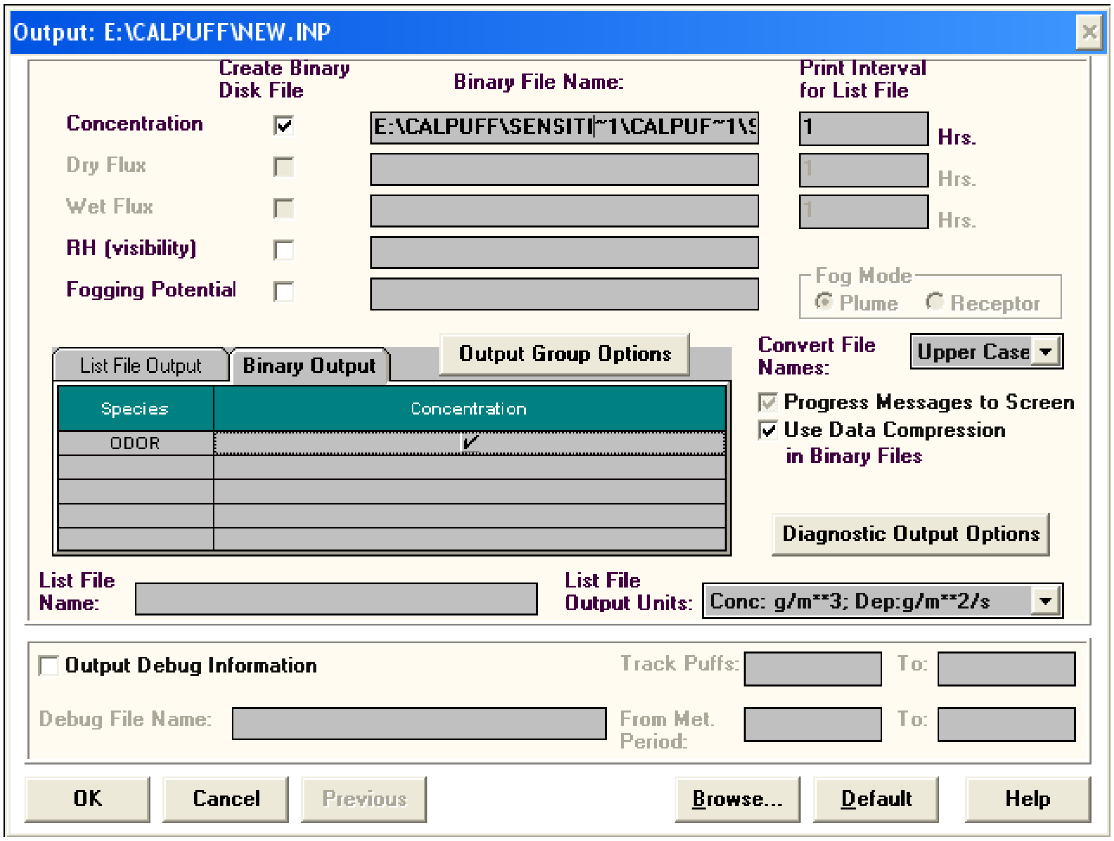
Screen 15: Gridded Receptors. The number of Grids will be automatically shown based on previous setting;



Screen 16: Discrete Receptors. No discrete receptor is involved;

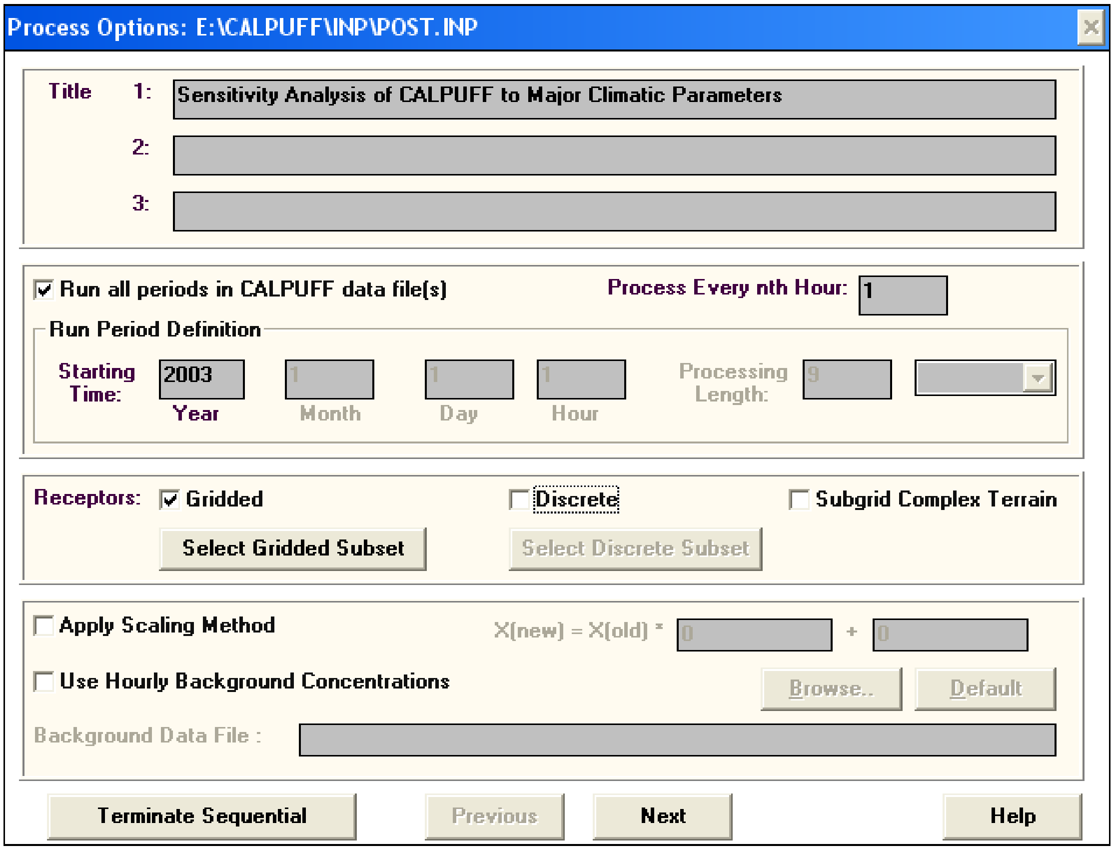


<u>Screen 17: Output</u>. Only Binary file for "Concentration" is specified with Pint Interval of 1 hr.

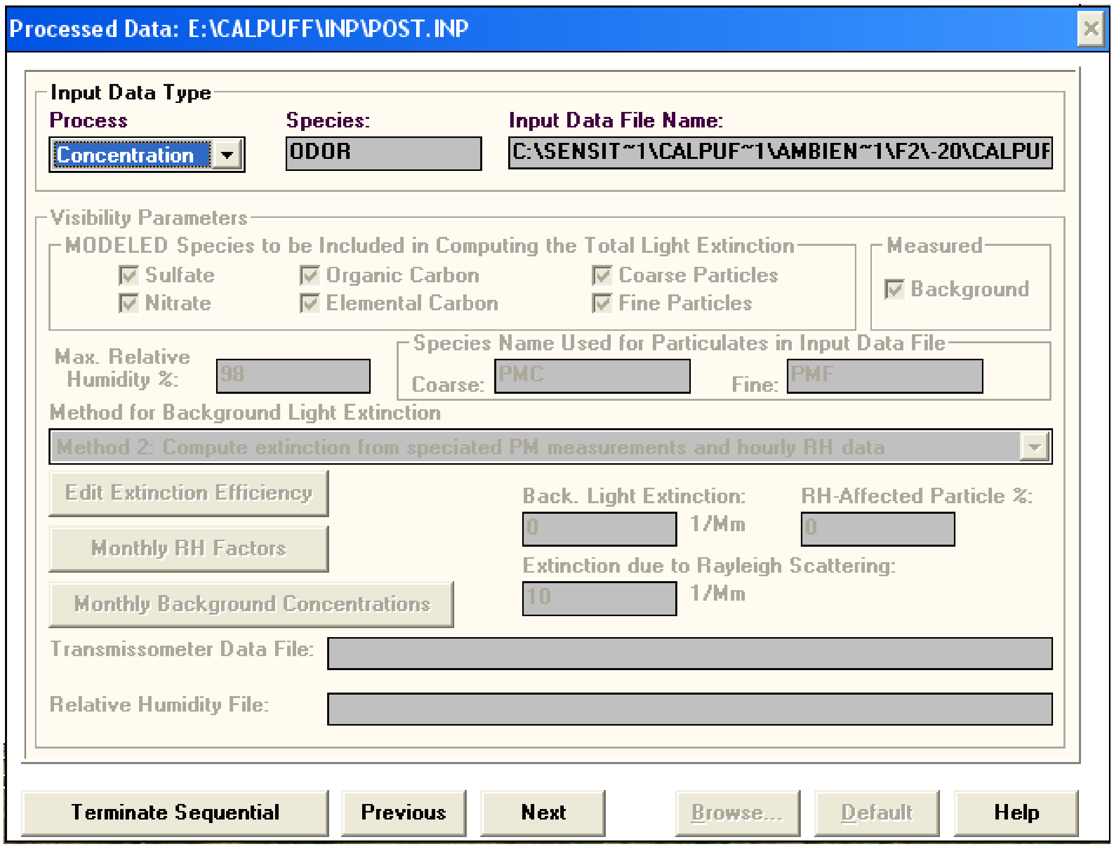


GUI run-stream file of CALPOST is shown as following part:

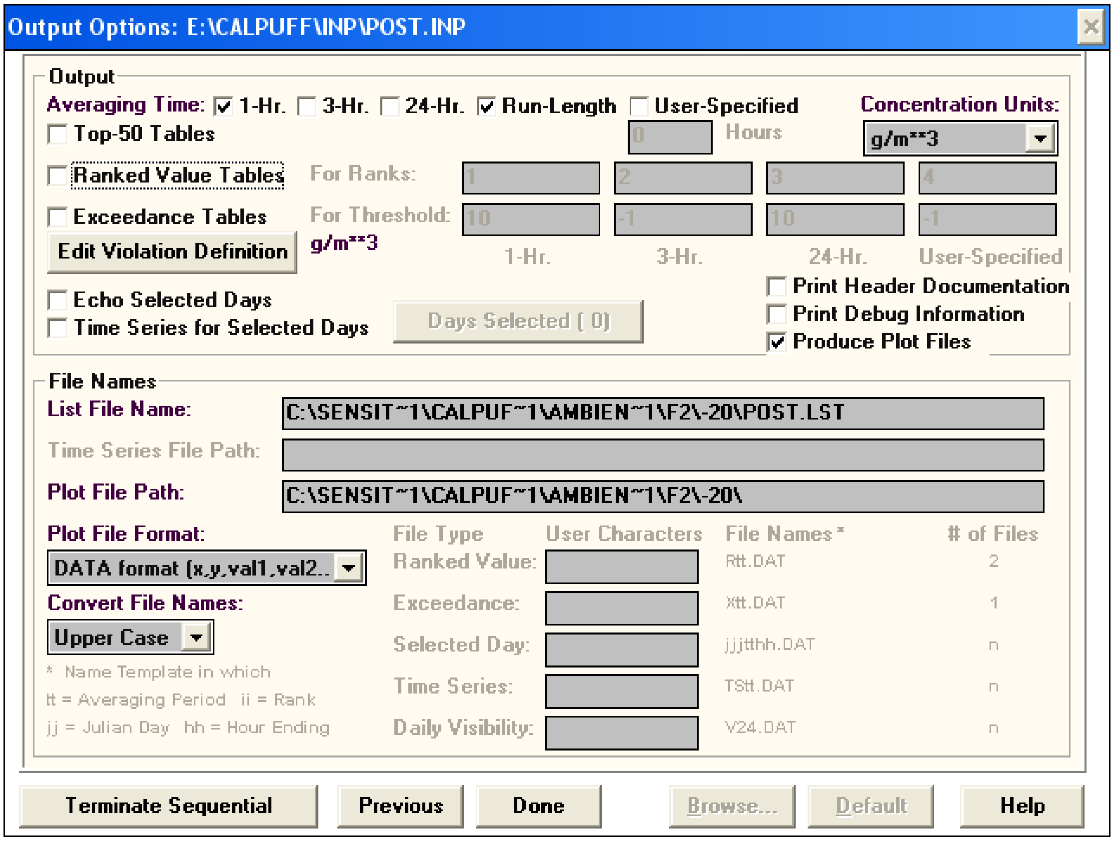
Screen 1: Process Option. Only one title was used here: Sensitivity analysis of CALPUFF to Major Climatic Parameters. Check the box of "Run all periods in CALPUFF data file(s)"; with "Process Every nth Hour" of 1. Provide the "Starting Time": 2003. Type of "Receptors" should be consistent with what used in CALPUFF*, so Gridded is checked. Others on this screen are retained as default;



<u>Screen 2: Processed Data</u>. In the box of "Input Data Type", Concentration is chosen, and "Species" was ODOR, and the name of CALPUFF* output file should be provided;



<u>Screen 3: Output Options</u>. For "Average Time", 1-Hr. and Run-length are checked. A name is provided to the CALPOST output in the box of "List File Name". Check the box in front of the "Produce Plot Files". A path is also given to the "Plot File Path". The outputs of CALPOST are the desired outcomes.



Appendix B: Run-stream Files of AERMOD V02222 (AERMET and AERMOD)

AERMOD of version 02222 were used in this part. Variables/parameters were specified according to the sensitivity simulation conditions in this part.

Run-stream files of AERMOD Version 02222 as a step by step example in the model sensitivity analysis was shown below:

To run AERMOD successfully, AERMET and AERMOD should be run in sequence. Both of them could be edited via a text editor. Three stages should be specified in AETMET to get the Surface File and Profiles File as following in this part:

Stage 1: Get the extracted surface observations and air soundings;

```
***________________________________***
JOB
        MESSAGES AERMET_S1.ERR
        REPORT AERMET_S1.RPT

UPPERAIR
        DATA AERMET_UA.FSL FSL
        EXTRACT AERMET_UA.IQA
        QAOUT AERMET_UA.OQA
        LOCATION 00099999 114.10 W 53.55N 6
        XDATES 03/06/22 03/06/22

        AUDIT UAPR UAHT UATT UATD UAWD UAWS

SURFACE
        DATA AERMET_SF.144 CD144
        EXTRACT AERMET_SF.IQA
        QAOUT AERMET_SF.OQA
        LOCATION 25000 113.82W 53.31N 0
        XDATES 03/06/22 03/06/22
***________________________________***
```

Notes:

1. JOB --- The file names for the message and report files;
2. UPPERAIR --- determined that NWS upper air soundings are to be processed and summarizes the information as follows:

   a) The input and output file names and if they were successfully opened;
   b) The station information (identifier, latitude, longitude and time conversion factor). In this part they are listed as "00099999 114.10 W 53.55N 6";
   c) The extract dates. In this part, they are listed as "03/06/22 03/06/22".

3. SURFACE --- determined that NWS hourly surface observations are to be processed and summarizes the information as follows:

   d) The input and output file names and if they were successfully opened;
   e) The station information (identifier, latitude, longitude and time conversion factor). For sensitivity analysis purpose in this part, they are listed as "25000 113.82W 53.31N 0";
   f) The extract dates. For sensitivity analysis purpose in this part, they are listed as "03/06/22 03/06/22".

Stage 2: Get QA'd surface observations and air soundings;

```
***________________________________***
JOB
     REPORT AERMET_S2.RPT
    MESSAGES AERMET_S2.ERR

UPPERAIR
    QAOUT AERMET_UA.OQA

SURFACE
    QAOUT AERMET_SF.OQA
```

```
MERGE
    OUTPUT AERMET_MR.MET
    XDATES 03/06/22 03/06/22
***________________________________***
```

Notes:

1. JOB --- The file names for the message and report files;

2. UPPERAIR --- output file name of upper air data if it was successfully processed;

3. SURFACE --- output file name of surface data if it was successfully processed;

4. MERGE --- output file name of merged data (upper air data and surface data) if it was successfully processed;

5. The extract dates. For sensitivity analysis purpose in this part, they are listed as “03/06/22 03/06/22”.

Stage 3: Get surface file and profile file;

```
***_________________________________***
JOB
    REPORT     AERMET_S3.RPT
    MESSAGES AERMET_S3.ERR

METPREP
    DATA AERMET_MR.MET
    OUTPUT AERMET_MP4.SFC
    PROFILE AERMET_MP4.PFL
   LOCATION 99999 113.82W 53.31N 6
    XDATES 03/06/22 03/06/22

    METHOD REFLEVEL SUBNWS
    METHOD WIND_DIR NORAND
    NWS_HGT WIND 10

    FREQ_SECT MONTHLY 1
    SECTOR 1 0 360
    SITE_CHAR 1 1 0.60 1.50 0.01
```

```
SITE_CHAR 2 1 0.60 1.50 0.01
SITE_CHAR 3 1 0.60 1.50 0.01
SITE_CHAR 4 1 0.60 1.50 0.01
SITE_CHAR 5 1 0.14 0.30 0.03
SITE_CHAR 6 1 0.14 0.30 0.03
SITE_CHAR 7 1 0.20 0.50 0.20
SITE_CHAR 8 1 0.20 0.50 0.20
SITE_CHAR 9 1 0.20 0.50 0.20
SITE_CHAR 10 1 0.18 0.70 0.05
SITE_CHAR 11 1 0.60 1.50 0.01
SITE_CHAR 12 1 0.60 1.50 0.01
```

____

Notes:

1. JOB --- The file names for the message and report files;

2. METPREP --- Determined the output files as followings:

   a) Output file name of surface data and profile data if it was successfully processed;
   b) The station information (identifier, latitude, longitude and time conversion factor). For sensitivity analysis purpose in this part, they are listed as “25000 113.82W 53.31N 6”;
   c) The extract dates. For sensitivity analysis purpose in this part, they are listed as “03/06/22 03/06/22”;
   d) Wind field parameters were determined according to simulation situation here. Under steady-state weather condition, wind direction was “NORAND”, while under variable weather condition, it was “RANDOM”;
   e) Three parameters, i.e., albedo, Bowen ratio, and surface roughness length, used in AETMET to define site characteristics in “SITE_CHAR”. For convenience, May to June was deemed as spring; July to September was deemed as summer; October was deemed as fall, and November to April next year was deemed as winter for the simulated area. According to Tables 4.3 to 4.5, typical values were given to these three parameters according to the different simulation season as above.

The input file needed to run the AERMOD model is based on a method that uses descriptive keywords that could be edited in a text editor. The run-stream file is divided into six functional "pathways." These pathways are identified by a two-character pathway ID placed at the beginning of each runstream image. The pathways and the order in which they are input to the model are as follows:

CO - for specifying overall job COntrol options;

SO - for specifying SOurce information;

RE - for specifying REceptor information;

ME - for specifying MEteorology information;

EV - for specifying EVent processing;

OU - for specifying OUtput options.

One example of runs-stream file for model sensitivity is shown as following:

```
***___________________________________________________________***
** SENSITIVITY ANALYSIS OF AERMOD TO MAJOR CLIMATIC PARAMETERS

CO STARTING
   TITLEONE ODOUR DISPERSION MODELING USING AERMOD MODEL
   TITLETWO UNDER STEADY STATE METEOROLOGICAL CONDITION
   MODELOPT DFAULT CONC
   AVERTIME 1 PERIOD
   POLLUTID OTHER
   FLAGPOLE 1.5
   RUNORNOT RUN
** RUN: RUN THE MODEL; NOT: PROCESS ONLY THE RUNTREAM FILE
   ERRORFIL RAMA.ERR
CO FINISHED
```

```
SO STARTING
SO ELEVUNIT METERS
** Axes                                   X (m), Y (m), Z (m)
SO LOCATION BARN (1) POINT -5.3125 64.9375 1.5
                        BARN (2) POINT 11.0625 64.9375 1.5
……………………………………………………………..
                        BARN (32) POINT 109.3125 114.0625 0
                        CELL (1) AREA -93.5 -23.5 0
                        CELL (2) AREA -117.5 -127.5 0
**PARAMETERS                Ptemis Stkhgt Stktmp Stkvel Stkdia
SO SRCPARAM BARN (1) 13685.25 1.5 296 0.05 16.375
                           BARN (2) 13685.25 1.5 296 0.05 16.375
**PARAMETERS                Aremis Relhgt Xinit Yinit Angle Szinit
                           CELL (1) 41.80 0 75 75 0 0
                           CELL (2) 33.25 0 99 99 0 0
SO SRCGROUP ALL
SO FINISHED

RE STARTING
RE ELEVUNIT METERS
RE GRIDCART Netid STA
                                  XYINC -24000 400 50 -24000 400 50
                                  END

ME STARTING
ME SURFFILE AERMET_MP4.SFC free
ME PROFFILE AERMET_MP4.PFL free
ME SURFDATA 25000 2003 Calmar
ME UAIRDATA 00099999 2003 Calmar
ME SITEDATA 0 2003 Calmar
ME PROFBASE 715
ME FINISHED

OU STARTING
OU RECTABLE 1 first-third
OU PLOTFILE period ALL AVERAGE.txt
OU FINISHED
```

____

Output of AERMOD, i.e., AVERAGE.txt is the desired result.

Appendix C: Detailed Agreement Analysis Results of Modeled and Measured Odour Intensity Using Minnesota Odour Plume Data

Table C.1 AERMOD predicted and all field measured odour intensity comparison using conversion equation from University of Minnesota for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity						Total No.	No. of agreed	% of agreement
	0	1	2	3	4	5			
100 m									
0	**38**	0	0	0	0	0	38	38	100
1	64	**5**	0	0	0	0	69	5	7
2	32	2	**0**	0	0	0	34	0	0
3	8	5	0	**0**	0	0	13	0	0
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							154	43	28
200 m									
0	**6**	0	0	0	0	0	6	6	100
1	13	**1**	0	0	0	0	14	1	7
2	5	3	**0**	0	0	0	8	0	0
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							28	7	25
300 m									
0	**1**	0	0	0	0	0	1	1	100
1	10	**0**	0	0	0	0	10	0	0
2	3	0	**0**	0	0	0	3	0	0
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							14	1	7.1

Table C.2 CALPUFF predicted and all field measured odour intensity comparison using conversion equation from University of Minnesota for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity						Total No.	No. of agreed	% of agreement
	0	1	2	3	4	5			
100 m									
0	**35**	3	0	0	0	0	38	35	92
1	62	**7**	0	0	0	0	69	7	10
2	28	5	**1**	0	0	0	34	1	3
3	7	2	4	**0**	0	0	13	0	0
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							154	43	28
200 m									
0	**5**	1	0	0	0	0	6	5	83
1	9	**4**	1	0	0	0	14	4	29
2	1	4	**3**	0	0	0	8	3	38
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							28	12	43
300 m									
0	**1**	0	0	0	0	0	1	1	100
1	6	**4**	0	0	0	0	10	4	40
2	2	1	**0**	0	0	0	3	0	0
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	---
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							14	5	35.7

Table C.3 AERMOD predicted and all filed measured odour intensity comparison using conversion equation from University of Minnesota with scaling factor for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity						Total No.	No. of agreed	% of agreement
	0	1	2	3	4	5			
100 m									
0	**27**	6	5	0	0	0	38	27	71
1	22	**28**	14	0	0	0	69	28	41
2	11	10	**11**	0	0	0	34	11	32
3	3	4	6	**0**	0	0	13	0	0
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
	0 - 5						154	66	43
200 m									
0	**5**	2	1	0	0	0	8	5	63
1	4	**5**	3	0	0	0	12	5	42
2	1	2	**5**	0	0	0	8	5	63
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	0	0	0	0	--
5	0	0	0	0	0	0	0	0	--
	0 - 5						28	15	54
300 m									
0	**0**	0	1	0	0	0	1	0	0
1	0	**3**	4	0	0	0	7	3	43
2	0	4	**2**	0	0	0	6	2	33
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
	0 - 5						14	5	35.7

Table C.4 CALPUFF predicted and all field measured odour intensity comparison using conversion equation from University of Minnesota with scaling factor for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity						Total No.	No. of agreed	% of agreement
	0	1	2	3	4	5			
100 m									
0	**27**	6	5	0	0	0	38	27	71
1	38	**18**	12	1	0	0	69	18	26
2	11	11	**7**	5	0	0	34	7	21
3	3	2	4	**4**	0	0	13	4	31
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							154	56	36
200 m									
0	**5**	0	1	0	0	0	6	5	83
1	8	**0**	3	3	0	0	14	0	0
2	1	0	**4**	3	0	0	8	4	50
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							28	9	32
300 m									
0	**0**	1	0	0	0	0	1	0	0
1	0	**6**	3	0	0	0	9	6	67
2	0	2	**2**	0	0	0	4	2	50
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							14	8	57

Table C.5 AERMOD predicted and all field measured odour intensity comparison using conversion equation from University of Alberta for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity						Total No.	No. of agreed	% of agreement
	0	1	2	3	4	5			
100 m									
0	**29**	4	2	3	0	0	38	29	76
1	42	**8**	3	11	5	0	69	8	12
2	18	3	**3**	8	2	0	34	3	9
3	7	0	0	**3**	3	0	13	3	23
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							154	43	28
200 m									
0	**5**	0	1	0	0	0	6	5	83
1	8	**0**	3	3	0	0	14	0	0
2	1	0	**4**	1	2	0	8	4	50
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							28	9	32
300 m									
0	**0**	0	0	1	0	0	1	0	0
1	0	**0**	4	6	0	0	10	0	0
2	0	0	**1**	2	0	0	3	1	33
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							14	1	7.1

Table C.6 CALPUFF predicted and all field measured odour intensity comparison using conversion equation from University of Alberta for Minnesota odour plume data

Measured odour intensity	Predicted odour intensity 0	1	2	3	4	5	Total No.	No. of agreed	% of agreement
100 m									
0	**32**	2	1	1	2	0	38	32	84.21
1	42	**9**	5	9	4	0	69	9	13.04
2	14	5	**4**	5	4	2	34	4	11.76
3	4	3	0	**1**	1	4	13	1	7.69
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							154	46	29.87
200 m									
0	**5**	0	0	0	1	0	6	5	83.33
1	8	**0**	0	2	2	2	14	0	0
2	1	0	**0**	0	4	3	8	0	0
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							28	5	17.86
300 m									
0	**0**	0	1	0	0	0	1	0	0
1	0	**0**	6	0	4	0	10	0	0
2	0	0	**1**	1	1	0	3	1	33.3
3	0	0	0	**0**	0	0	0	0	--
4	0	0	0	0	**0**	0	0	0	--
5	0	0	0	0	0	**0**	0	0	--
Total 0 - 5							14	1	7.14

Appendix D: Detailed Agreement Analysis Results of Modeled and Measured Odour Intensity Using Alberta Odour Plume Data

Table D.1 AERMOD predicted and all measured odour intensity comparison using conversion equation from University of Minnesota for Alberta odour plume data

Measured odour intensity	Predicted odour intensity							Total No.	No. of agreed	% of agreement
	0	1 - 3	4	5	6	7	8			
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	2	**0**	0	0	0	0	0	2	0	0
4	1	0	**0**	0	0	0	0	1	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	3	0	0	0	**0**	0	0	3	0	0
7	3	0	0	0	0	**0**	0	3	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	0	0
300 m										
0	**1**	0	0	0	0	0	0	1	1	100
1 - 3	11	**6**	0	0	0	0	0	17	6	35
4	9	1	**0**	0	0	0	0	10	0	0
5	6	2	0	**0**	0	0	0	8	0	0
6	5	0	0	0	**0**	0	0	5	0	0
7	2	0	0	0	0	**0**	0	2	0	0
8	1	0	0	0	0	0	**0**	1	0	0
Total 0 - 8								44	7	16
500 m										
0	**16**	5	0	0	0	0	0	21	16	76
1 - 3	68	**6**	0	0	0	0	0	74	6	8
4	15	0	**0**	0	0	0	0	15	0	0
5	5	1	0	**0**	0	0	0	6	0	0
6	5	1	0	0	**0**	0	0	6	0	0
7	1	0	0	0	0	**0**	0	1	0	0
8	1	0	0	0	0	0	**0**	1	0	0
Total 0 - 8								124	22	18

(To be continued)

					800 m					
Measured odour intensity	Predicted odour intensity							Total No.	No. of agreed	% of agreement
	0	1 - 3	4	5	6	7	8			
0	**21**	0	0	0	0	0	0	21	21	100
1 - 3	52	**0**	0	0	0	0	0	52	0	0
4	4	0	**0**	0	0	0	0	4	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	2	0	0	0	**0**	0	0	2	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	21	26

Table D.2 CALPUFF predicted and all measured odour intensity comparison using conversion equation from University of Minnesota for Alberta odour plume data

Measured odour intensity	Predicted odour intensity 0	1 - 3	4	5	6	7	8	Total No.	No. of agreed	% of agreement
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	2	**0**	0	0	0	0	0	2	0	0
4	0	1	**0**	0	0	0	0	1	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	0	3	0	0	**0**	0	0	3	0	0
7	0	3	0	0	0	**0**	0	3	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	0	0
300 m										
0	**1**	0	0	0	0	0	0	1	1	100
1 - 3	10	**7**	0	0	0	0	0	17	7	41.18
4	6	4	**0**	0	0	0	0	10	0	0
5	3	5	0	**0**	0	0	0	8	0	0
6	4	1	0	0	**0**	0	0	5	0	0
7	1	1	0	0	0	**0**	0	2	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								44	8	18.19
500 m										
0	**15**	6	0	0	0	0	0	21	15	71.43
1 - 3	63	**11**	0	0	0	0	0	74	11	14.86
4	14	1	**0**	0	0	0	0	15	0	0
5	6	1	0	**0**	0	0	0	7	0	0
6	3	2	0	0	**0**	0	0	5	0	0
7	1	0	0	0	0	**0**	0	1	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								124	26	20.97
800 m										
0	**20**	1	0	0	0	0	0	21	20	95.24
1 - 3	49	**3**	0	0	0	0	0	52	3	5.77
4	3	1	**0**	0	0	0	0	4	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	2	0	0	0	**0**	0	0	2	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	23	28.75

Table D.3 AERMOD predicted and all measured odour intensity comparison using conversion equation from University of Minnesota with scaling factor for Alberta odour plume data

Measured odour intensity	Predicted odour intensity 0	1 - 3	4	5	6	7	8	Total No.	No. of agreed	% of agreement
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	2	**0**	0	0	0	0	0	2	0	0
4	0	1	**0**	0	0	0	0	1	0	0
5	0	1	0	**0**	0	0	0	1	0	0
6	0	3	0	0	**0**	0	0	3	0	0
7	0	3	0	0	0	**0**	0	3	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	0	0
300 m										
0	**1**	1	0	0	0	0	0	2	1	50
1 - 3	7	**6**	3	0	0	0	0	16	6	38
4	2	8	**0**	0	0	0	0	10	0	0
5	2	6	0	**0**	0	0	0	8	0	0
6	3	2	0	0	**0**	0	0	5	0	0
7	0	2	0	0	0	**0**	0	2	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								44	7	16
500 m										
0	**15**	3	3	0	0	0	0	21	15	71
1 - 3	45	**30**	0	0	0	0	0	75	30	40
4	8	6	**0**	0	0	0	0	14	0	0
5	2	3	1	**0**	0	0	0	6	0	0
6	2	4	0	0	**0**	0	0	6	0	0
7	0	1	0	0	0	**0**	0	1	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								124	45	36
800 m										
0	**19**	2	0	0	0	0	0	21	19	90
1 - 3	34	**18**	0	0	0	0	0	52	18	35
4	3	1	**0**	0	0	0	0	4	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	2	0	0	0	**0**	0	0	2	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	37	46

Table D.4 CALPUFF predicted and all measured odour intensity comparison using conversion equation from University of Minnesota with scaling factor for Alberta odour plume data

Measured odour intensity	Predicted odour intensity 0	1 - 3	4	5	6	7	8	Total No.	No. of agreed	% of agreement
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	0	**2**	0	0	0	0	0	2	2	100
4	0	1	**0**	0	0	0	0	1	0	0
5	0	1	0	**0**	0	0	0	1	0	0
6	0	3	0	0	**0**	0	0	3	0	0
7	0	3	0	0	0	**0**	0	3	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	2	20
300 m										
0	**1**	1	0	0	0	3	0	5	1	20
1 - 3	6	**6**	1	3	0	0	0	16	6	38
4	2	8	**0**	0	0	0	0	10	0	0
5	1	7	0	**0**	0	0	0	8	0	0
6	2	3	0	0	**0**	0	0	5	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								44	7	16
500 m										
0	**13**	5	3	0	0	0	0	21	13	62
1 - 3	32	**36**	6	0	0	0	0	74	36	49
4	2	13	**0**	0	0	0	0	15	0	0
5	1	4	1	**0**	0	0	0	6	0	0
6	0	5	1	0	**0**	0	0	6	0	0
7	0	1	0	0	0	**0**	0	1	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								124	39	31
800 m										
0	**15**	6	0	0	0	0	0	21	15	71
1 - 3	29	**22**	1	0	0	0	0	52	22	42
4	2	2	**0**	0	0	0	0	4	0	0
5	0	1	0	**0**	0	0	0	1	0	0
6	1	1	0	0	**0**	0	0	2	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	37	46

Table D.5 AERMOD predicted and all measured odour intensity comparison using conversion equation from University of Alberta for Alberta odour plume data

Measured odour intensity	Predicted odour intensity							Total No.	No. of agreed	% of agreement
	0	1 - 3	4	5	6	7	8			
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	1	**1**	0	0	0	0	0	2	1	50
4	0	1	**0**	0	0	0	0	1	0	0
5	0	1	0	**0**	0	0	0	1	0	0
6	0	3	0	0	**0**	0	0	3	0	0
7	0	3	0	0	0	**0**	0	3	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	1	10
300 m										
0	**1**	0	0	0	1	0	0	2	1	50
1 - 3	8	**3**	2	1	2	0	0	16	3	19
4	2	7	**1**	0	0	0	0	10	1	10
5	1	6	1	**0**	0	0	0	8	0	0
6	3	2	0	0	**0**	0	0	5	0	0
7	0	2	0	0	0	**0**	0	2	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								44	5	11
500 m										
0	**14**	2	2	2	1	0	0	21	14	67
1 - 3	44	**26**	3	2	0	0	0	75	26	35
4	7	7	**0**	0	0	0	0	14	0	0
5	1	4	0	**1**	0	0	0	6	1	17
6	1	4	1	0	**0**	0	0	6	0	0
7	0	1	0	0	0	**0**	0	1	0	0
8	0	1	0	0	0	0	**0**	1	0	0
Total 0 - 8								124	40	32
800 m										
0	**19**	2	0	0	0	0	0	21	19	90
1 - 3	32	**19**	0	1	0	0	0	51	19	37
4	3	1	**0**	0	0	0	0	4	0	0
5	1	0	0	**0**	0	0	0	1	0	0
6	2	0	0	0	**0**	0	0	2	0	0
7	0	0	0	0	0	**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	38	48

Table D.6 CALPUFF predicted and all measured odour intensity comparison using conversion equation from University of Alberta for Alberta odour plume data

Measured odour intensity	Predicted odour intensity 0	1 - 3	4	5	6	7	8	Total No.	No. of agreed	% of agreement
200 m										
0	**0**	0	0	0	0	0	0	0	0	--
1 - 3	0	**2**	0	0	0	0	0	2	2	100
4	0	0	**1**	0	0	0	0	1	1	100
5	0	1	2	**0**	0	0	0	3	0	0
6	0	0	3	0	**0**	0	0	3	0	0
7	0	0	1	0	0	**0**	0	1	0	0
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								10	3	30
300 m										
0	**1**	0	0	0	0	0	0	1	1	100
1 - 3	7	**3**	3	0	1	3	0	17	3	17.65
4	2	5	**2**	1	0	0	0	10	2	20
5	1	3	3	**1**	0	0	0	8	1	12.5
6	2	2	1	0	**0**	0	0	5	0	0
7	0	1	1	0	0	**0**	0	2	0	0
8	0	0	1	0	0	0	**0**	1	0	0
Total 0 - 8								44	7	15.91
500 m										
0	**13**	4	1	3	0	0	0	21	13	61.9
1 - 3	32	**31**	5	6	0	0	0	74	31	41.89
4	2	13	**0**	0	0	0	0	15	0	0
5	1	4	0	**0**	1	0	0	6	0	0
6	0	4	1	1	**0**	0	0	6	0	0
7	0	1	0	0	0	**0**	0	1	0	0
8	0	0	1	0	0	0	**0**	1	0	0
Total 0 - 8								124	44	35.48
800 m										
0	**13**	7	1	0	0	0	0	21	13	61.9
1 - 3	29	**21**	1	1	0	0	0	52	21	40.38
4	2	2	**0**	0	0	0	0	4	0	0
5	0	1	0	**0**	0	0	0	1	0	0
6	1	1	0	0	**0**	0	0	2	0	0
7	0	0	0	0		**0**	0	0	0	--
8	0	0	0	0	0	0	**0**	0	0	--
Total 0 - 8								80	34	42.5