Sensitivity analysis of a livestock odour dispersion model (LODM) to input parameters, Part 1: Source parameters and surface parameters

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http://dx.doi.org/10.7451/CBE.2013.55.6.1

Yu, Z., H. Guo and C. Laguë. 2013. **Sensitivity analysis of a livestock odour dispersion model (LODM) to input parameters, Part 1: Source parameters and surface parametersl**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **55**: 6.1-6.11. Sensitivity analysis was conducted to evaluate a livestock odour dispersion model (LODM) with respect to its input source parameters including: stack height, stack diameter, exit velocity, exit temperature, and emission rate and surface parameters (surface roughness, albedo, and Bowen ratio). An elasticity value was calculated together with the average change of odour concentration and frequency to indicate the model sensitivity to its input parameters. Results showed that the source parameters have the similar medium impact on model predicted hourly odour concentrations and hourly odour frequencies. The sensitivity of emission rate is lower to odour frequencies than odour concentrations. Among the three surface parameters, LODM has low sensitive to surface roughness while its sensitivity to albedo and Bowen ratio is negligible. In practice, in order to reduce the odour impact from livestock operation, the most effective way is to reduce the emission rate. **Keywords:** Livestock odour dispersion model, sensitivity analysis, odour emission rate, surface roughness

Une analyse de sensibilité a été faite pour évaluer un modèle de dispersion d'odeur provenant d'élevage (LODM) prenant en compte ses intrants qui incluent: la hauteur de sortie de ventilation, le diamètre de sortie de ventilation, la vitesse de sortie, la température à la sortie, le taux d'émission et les paramètres du surface (rugosité de surface, albedo et ratio Bowen). Une valeur d'élasticité a été calculée ainsi que la moyenne des changements de concentration et fréquence d'odeur pour indiquer la sensibilité du modèle en relation aux intrants. Les résultats ont montré que les intrants ont un impact moyen similaire sur la prédiction horaire des concentrations et des fréquences d'odeur obtenue par le modèle. La sensibilité du taux d'émission est plus faible pour les fréquences d'odeur que pour les concentrations d'odeur. Pour ce qui est des trois paramètres de surface, LODM a une sensibilité faible à la rugosité de surface et sa sensibilité est négligeable à l'albedo et au ratio Bowen. En pratique, de manière à réduire l'impact des odeurs d'élevage, le moyen le plus efficace est de réduire le taux d'émission. **Mots clés:** modèle de dispersion des odeurs d'élevage, analyse de sensibilité, taux d'émission d'odeur, rugosité de surface

INTRODUCTION

The increasing odour complaints from the nearby communities have been an obstacle for the development of livestock industry. One of the tools that have been used to deal with odour problems is air dispersion model. Most of the existing air dispersion models such as ISCST3, CALPUFF, and AERMOD were designed for the industrial air pollution. Livestock odour is different from traditional air pollutants in emission, dispersion, and reception. The most important characteristics of odour (e.g. livestock odour) is that it can be detected by receptors when exceeding the odour threshold in a few seconds, even though the hourly mean odour concentration is below the odour threshold. Therefore, the hourly averaged mean concentration predicted by most of the air dispersion models cannot be used to fully evaluate the odour impact, thus it hinder the application of the existing air dispersion models (Yu et al. 2010).

A livestock odour dispersion model (LODM) was developed based on the fluctuating plume model. It is capable of considering short time odour fluctuations and predicting hourly mean odour concentration and hourly odour frequency with input of hourly averaged meteorological data (Yu et al. 2011a). The hourly odour frequency is defined as the frequency of short time odour concentration equaling to or exceeding an odour threshold (1 OU/m^3 in this paper). This model was designed specifically for livestock odour with the features such as dealing with different kinds of and multiple sources, varied emission rate, relationship between odour intensity and concentration. The validation with two sets of field odour plume measurement data showed that the model is adequate in predicting both odour concentration and frequency (Yu et al. 2011b).

Sensitivity analysis is a necessary component in the evaluation of the model to understand the behaviours of a model with respect to input parameters. It can be conducted to verify the validity of the model, determine the important parameters to have more accurate values, and understand

the behaviours of the system being modeled (Horwedel et al. 1992; Smith 1993). The required input parameters of LODM can be separated into three categories: source parameters, surface parameters, and meteorological parameters. When simulating a point source, the source parameters involved are emission rate, stack height, stack diameter, exit velocity, and exit temperature. The surface parameters engaged are surface roughness, albedo, and Bowen ratio. The meteorological parameters include wind speed, wind direction, ambient temperature, stability class, mixing height, or radiation and cloud cover. There is some other additional information required such as the location, time zone of the site, and the reference height of the anemometer. For existing livestock operations, once the odour problem occurs, effective ways should be taken to control the odour dispersion and mitigate the odour effect. Producers can control the odour either by enhancing the odour dispersion or reducing odour emissions. Therefore, the model sensitivity to the controllable source parameters by producers such as stack height, exit temperature, stack diameter, exit velocity, as well as emission rate is very important for the odour application. It is very obvious that increasing odour emission rate will increase the downwind odour concentration. Also, it is well known that higher stack height will decrease the ground level concentration of odour. Smith (1993) assessed the sensitivity of the concentration prediction of STINK model to variation in the model parameters and concluded that odour emission rate is one of the most important variables in the prediction of downwind concentration. The surface parameters, e.g. surface roughness, albedo, and Bowen ratio, are important inputs of LODM. These parameters are not directly measured at meteorological monitoring stations. Determination of these parameters for modeling site is somewhat subjective and there are no clear guidelines, therefore, it is important to find out how accurately these parameters need to be specified by conducting sensitivity analysis (Long et al. 2004). Long et al. (2004) and Karvounis et al. (2007) pointed out AERMOD is very sensitive to surface roughness and rather indifferent to albedo and Bowen ratio. Grosch and Lee (1999) concluded that changes in albedo, Bowen ratio, and surface roughness length can result in changes in design concentrations of factors of 1.5, 2.6, and 160, respectively. In a study of Faulkner et al. (2008), it showed that AERMOD is sensitive to changes in albedo and surface roughness but Bowen ratio did not affect the results from AERMOD. All the past studies focused on the model sensitivity of predicting pollutant's averaged concentrations, no study has been done to explore the sensitivity of model predicted frequency to the input parameters.

The objective of this paper as first part of the LODM sensitivity analysis is to present sensitivity of LODM to the input source parameters and surface parameters. The model sensitivity to meteorological parameters will be conducted and documented in the part two of this study.

MATERIALS AND METHODS

Location of simulations

A virtual point source was placed at 150 km west of Saskatoon, Saskatchewan, Canada (52.167 N, 108.687 W), where a typical swine farm located. The time zone of this location is identified by -6 hours from GMT. The wind speed was assumed to be measured at height 10 m above the ground level, while the ambient temperature, wind speed, wind direction were assumed to be observed at 2 m above the ground level.

LODM

LODM is an odour dispersion model designed specifically for livestock facilities. It has the ability to predict hourly odour frequency with input hourly meteorological data based on the Gaussian fluctuating plume model (Yu et al. 2011a). The hourly odour frequency is estimated by a weighted odour exceeding half width method adapted from Hogström (Högström 1972). The prediction of hourly odour frequency was based on horizontal and vertical distributions of the centroid of a plume within which the odour concentration equals to or exceeds the defined odour threshold (e.g. 1 OU/m^3). The plume has to be confined to a maximum height in order for the receptor to reach the plume vertically. The distance between the ground level and the maximum height is divided into N equal spaces (N = 100, in LODM) in order to estimate the weighted odour exceeding half width, which will then be used to estimate the hourly odour frequency. Therefore, a pseudo short averaging period is found by dividing 1 hour by N, which results in 36 s. The increasing of number N will achieve shorter pseudo short averaging period, while it will increase the computing time. The detail of the weighted odor exceeding half width method can be found in Yu et al. (2011a). The Hogström's dispersion coefficients are applied in LODM. A stability index different from Pasquill-Gifford stability class was defined.

$$s = \left(\frac{\partial \theta}{\partial z} \Big/ u_f^2 \right) \cdot 10^5 \quad (1)$$

in which $\partial\theta/\partial z$ is the vertical gradient of potential temperature at the level of the plume centre, K m^{-1}; u_f is the wind speed at the top of friction layer, m/s. Both parameters cannot be obtained directly from routinely observed meteorological data. Therefore, the profile of vertical gradient of temperature and the profile of wind speed need to be characterized. The Monin-Obukhov similarity theory was used to estimate the vertical profile of wind speed and vertical gradient of potential temperature which determine the Hogstrŏm stability parameter (s). The Monin-Obukhov similarity theory has been widely accepted to characterize Planetary Boundary Layer (PBL) (Arya 1999). The parameters representing the boundary layer are friction velocity (u_*), Monin-Obukhov length (L_{mo}), friction temperature (θ_*), mixing height (z_i), and surface heat flux (H_S). These parameters can be derived both in the convective boundary layer (CBL) and stable boundary layer (SBL). The methods used to derive the

parameters as well as profile of vertical gradient of potential temperature and wind speed are following those used in AERMOD model (USEPA 2004). These parameters are functions of meteorological conditions and the surface characteristics. Therefore, surface parameters, namely surface roughness, albedo, and Bowen ratio, are essential input for LODM to predict odour concentration and frequency. When LODM is used to model elevated odour source, the stack-tip downwash and plume rise will be estimated following the method used in ISC model (USEPA 1995). The stack diameter, exit velocity, and exit temperature are the determined factors of plume rise, thus they will have effects on model calculations.

Sensitivity analysis

The sensitivity of estimates of odour concentration and frequency to a particular variable/parameter is the change in the estimate with respect to a change in the value of the parameter while keeping all other parameters constant (Smith 1993).

The sensitivity was expressed as an elasticity, S, which is defined as the percentage change in the concentration or frequency for a 1% change in the parameter value. The average sensitivity was determined using the sensitivity index of Ng and Loomis (1984), as cited by Smith (1993).

$$S_{av} = \frac{100}{N\Delta}\sum_{1}^{N}\frac{C_{ni}-C_{ci}}{C_{ci}} \qquad (2)$$

where N is the number of points (odour concentration or odour frequency) in the model output; Δ is the absolute change in the parameter value expressed as a percentage of its control value; C_{ni} is the new value of the concentration or frequency for i^{th} point with a changed value of the input parameter; C_{ci} is the corresponding value at i^{th} point in the control simulation. For example, S = 0.1 would mean that for each percent change of the input parameter, on an average, the output increases by 0.1 %; while S = -0.1 would mean that the output decreases by 0.1 %. When calculating the elasticity value, the receptors on which the predicted hourly odour concentration less than 0.1 OU/m^3 were excluded to avoid the inappropriately large elasticity values usually found close to the source. The large elasticity values are resulted from the low concentrations due to the plume rise. The sensitivity of the model predicted odour concentration and frequency to input parameters can be rated as: high ($|S| > 0.5$), medium ($0.1 < |S| < 0.5$), low ($0.01 < |S| < 0.1$), and indifferent ($|S| < 0.01$), in which $|S|$ is the absolute value of S. The odour concentrations and odour frequency at the 231 downwind receptors that cover the downwind area of 1000 m width and 5000 m length as shown in Fig. 1 were estimated to conduct the sensitivity analysis. A base case was set as shown in Table 1 to reflect the typical setting of modelling a livestock odour source as point source. Livestock odour sources are usually treated as volume or area sources in air dispersion modelling. In LODM, no plume rise calculation

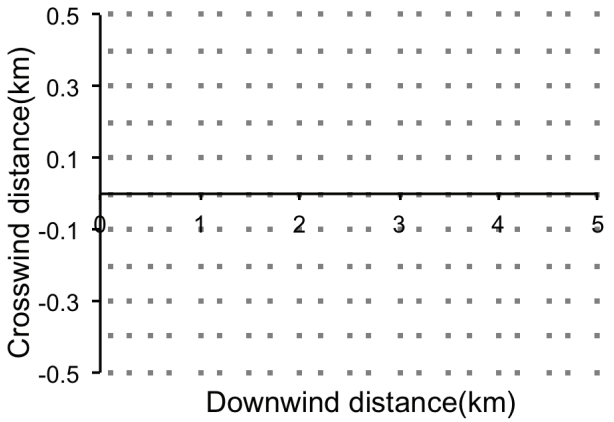

Fig. 1. Layout of 231 downwind receptors (each symbol represents a receptor with a height of 1.5 m).

Table 1. Input parameters and their variations for sensitivity analysis.

Input parameter	Base case	Variation*
Source parameters		
Emission rate	500,000 OU/s	±50% · BC
Stack height	2 m	±50% · BC
Stack diameter	3 m	±50% · BC
Exit velocity	0.5 m/s	±50% · BC
Exit temperature	22 ℃	± 2 ℃
Surface parameters		
Surface roughness	0.1 m	0.01 m, 0.5 m, 1 m, 1.5 m
Albedo	0.18	0.1, 0.2, 0.3, 0.4, 0.5, 0.6
Bowen ratio	0.8	0.1, 0.5, 1, 5, 10
Meteorological parameters		
Ambient temperature	20 ℃	Constant
Wind speed	2.5 m/s	Constant
Wind direction	90°	Constant
Stability Class	C, D, and E	Constant
Mixing height	1000 m	Constant

*BC refers to base case.

Table 2. Sensitivity analysis of odour concentration and frequency to stack height with a control value of 2 m.

Stability	Change, %	Concentration				Frequency			
		Ave. C Change, %	S(0.5)	S(5)	S(ave)	Ave. F Change, %	S(0.5)	S(5)	S(ave)
Unstable	-50	23.8	0.44	0.42	0.42	4.4	0.07	0.11	0.09
	50	-14.7	-0.28	-0.29	-0.29	-3.8	-0.07	-0.10	-0.08
Neutral	-50	32.3	0.64	0.64	0.64	5.0	0.16	0.12	0.13
	50	-17.4	-0.33	-0.32	-0.33	-3.5	-0.12	-0.08	-0.09
Stable	-50	35.6	0.68	0.66	0.66	3.9	0.12	0.09	0.09
	50	-24.0	-0.42	-0.38	-0.39	-2.5	-0.11	-0.06	-0.06

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

is involved for volume or area source, thus the only input source parameter beside the location and emission rate is the effective height of the source. However, the animal barn can also be treated as many point sources by allocating the total emission rates into individual point source (Xing et al. 2007). In order to simplify the sensitivity analysis, a simple point source with a stack height of 2 m, a stack diameter of 3 m, an exit velocity of 0.5 m/s, and an exit temperature of 22°C were utilized to represent the livestock odour source. The emission rate of a typical swine barn in Saskatchewan varied from 219,693 OU/s to 967,556 OU/s during the warm season (May to Oct.) (Guo et al. 2006), therefore the base emission rate in the simulation was set to be 500,000 OU/s. The base of surface parameters was selected for grassland in summer season (USEPA 2004). Since the surface parameters (surface roughness, albedo, Bowen ratio) are interrelated, it needs to be cautious when selecting different combinations of these parameters in simulations. Some combinations are not realistic in the real world; for example, water surface has a surface roughness length of 0.0001, it is not realistic to combine it with a Bowen ratio of 10, which represents a very dry surface. The meteorological parameters such as ambient temperature, wind speed, wind direction, and mixing height were set to be constant. And the sensitivity analysis was conducted under three different stability conditions (unstable: Stability class = C; neutral: Stability class = D; and stable: Stability class = E). The variation of source parameters and surface parameters can be also found from Table 1. The elasticity (S) for each surface and source parameter was calculated. The changes in average concentration and frequency with the changing input parameter were also calculated. The changes of centerline odour concentration and odour frequency with the changes of input parameters were also plotted to demonstrate the sensitivity of input parameter on centerline odour concentration and odour frequency.

RESULTS

Source parameters

Stack height Stack height is a very important parameter affecting downwind odour concentration and frequency. The higher the stack height, the lower is the concentration and the frequency that can be detected at ground level.

From Figs. 2 and 3, the centerline odour concentrations and odour frequencies increase when stack height decreases from 2 m to 1 m, while they decrease when

Table 3. Sensitivity analysis of odour concentration and frequency to stack diameter with a control value of 3 m.

Stability	Change, %	Concentration				Frequency			
		Ave. C Change, %	S(0.5)	S(5)	S(ave)	Ave. F Change, %	S(0.5)	S(5)	S(ave)
Unstable	-50	18.4	0.40	0.51	0.45	4.9	0.10	0.14	0.11
	50	-11.8	-0.24	-0.30	-0.27	-3.7	-0.07	-0.10	-0.08
Neutral	-50	16.3	0.29	0.27	0.27	2.8	0.14	0.06	0.08
	50	-12.0	-0.20	-0.18	-0.19	-2.2	-0.12	-0.05	-0.06
Stable	-50	26.4	0.36	0.25	0.27	-1.1	0.05	-0.03	-0.02
	50	-16.3	-0.23	-0.14	-0.16	-0.2	-0.09	0.00	-0.01

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

Table 4. Sensitivity analysis of odour concentration and frequency to exit velocity with a control value of 0.5 m s^{-1}.

Stability	Change, %	Concentration				Frequency			
		Ave. C Change,%	S(0.5)	S(5)	S(ave)	Ave. F Change,%	S(0.5)	S(5)	S(ave)
Unstable	-50	18.4	0.40	0.46	0.44	4.9	0.10	0.12	0.10
	50	-11.8	-0.24	-0.28	-0.27	-3.7	-0.07	-0.09	-0.08
Neutral	-50	16.3	0.29	0.27	0.27	2.8	0.14	0.06	0.08
	50	-12.0	-0.20	-0.18	-0.19	-2.2	-0.12	-0.05	-0.06
Stable	-50	13.6	0.18	0.12	0.14	-0.4	0.04	-0.01	0.00
	50	-8.2	-0.11	-0.07	-0.08	0.0	-0.04	0.00	0.00

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

stack height changes from 2 m to 3 m. The average changes of odour concentrations and odour frequencies with the changes of stack height with a control value of 2 m and the elasticity values at 0.5 km downwind, 5 km downwind, and the average elasticity value are listed in Table 2. When stack height increased from 2 m to 3 m, the average odour concentrations decreased 14.7%, 17.4%, and 24.0% respectively for unstable, neutral, and stable conditions, while the average odour frequencies decreased from 3.8%, 3.4%, and 2.5%. However, if the stack height decreased from 2 m to 1 m, the average odour concentrations increased 23.8%, 32.3%, and 35.6% respectively for unstable, neutral, and stable conditions, while the average odour frequencies increased 4.4%, 5.0%, and 3.9%. The decreasing of stack height had greater effect on the odour concentrations and odour frequencies than the increasing of stack height, which was also confirmed by the elasticity values. The average elasticity values are 0.42, 0.64, and 0.66 for odour concentrations and 0.09, 0.13, and 0.09 for odour frequencies under the three different stability conditions when decreasing stack height. When increasing stack height, the averaged elasticity values were -0.29, -0.33, and -0.39 for odour concentrations and -0.08, -0.09, and -0.06 for odour frequencies. It also showed that the effect of changes of stack height on odour frequency was much less than that on odour concentrations. The elasticity values at distances of 0.5 km and 5 km were similar. The effect of changing stack height on model predictions was not sensitive to the downwind distances. Overall, the elasticity values indicate that stack height has medium sensitivity to the odour concentration and low sensitivity to odour frequency.

Stack diameter Stack diameter is an essential parameter when calculating plume rise. The changes of stack diameter while keeping other parameters constant could

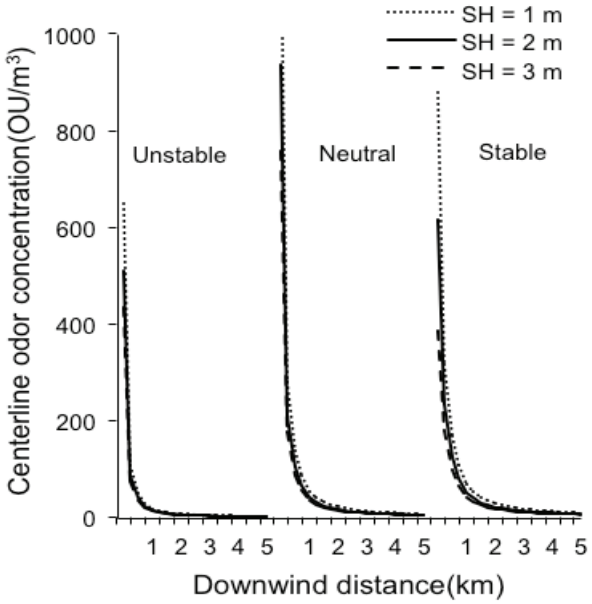

Fig. 2 Centerline odour concentrations for different stack heights (SH).

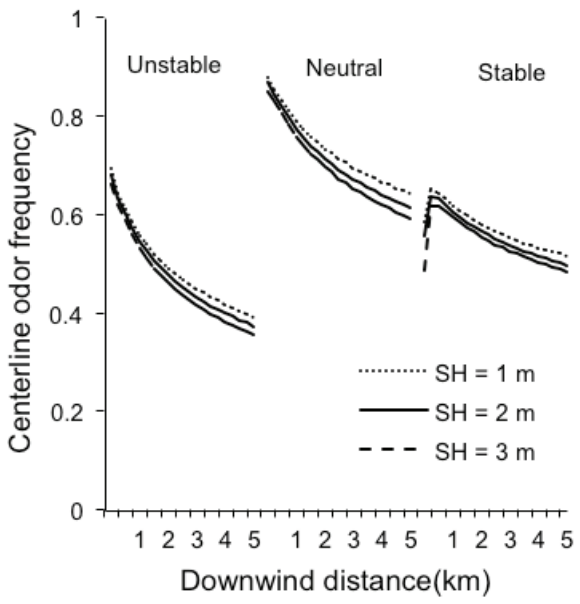

Fig. 3. Centerline odour frequencies for different stack heights (SH).

Table 5. Sensitivity analysis of odour concentration and frequency to exit temperature with a control value of 22°C.

Stability	Change, °C	Concentration				Frequency			
		Ave. C Change,%	S(0.5)	S(5)	S(ave)	Ave. F Change,%	S(0.5)	S(5)	S(ave)
Unstable	-2	4.6	0.00	0.00	0.01	0.1	0.00	0.00	0.00
	2	3.9	-0.58	-0.68	-0.44	1.1	-0.17	-0.20	-0.12
Neutral	-2	5.9	0.00	0.00	0.01	0.0	0.00	0.00	0.00
	2	3.8	-0.47	-0.43	-0.29	0.7	-0.24	-0.10	-0.09
Stable	-2	-98.4	4.50	3.26	2.36	-2.8	0.19	-0.44	-0.26
	2	16.0	-1.43	-0.91	-0.68	0.1	-0.54	0.03	-0.04

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

cause changes in odour concentration and frequency, as shown in Figs. 4 and 5. It should be noted that under stable condition, the effect of changing stack diameter on odour frequency was different from under unstable and neutral conditions. It can be seen from Fig. 5 after a certain distance, the odour frequency decreased when the stack diameter decreased from 3 m to 1.5 m, while it increased under unstable and neutral conditions. Based on the fluctuating plume theory, the odour frequency was determined by calculating the chances of fluctuating odour plume touching the receptor. The effect of input source parameters on odour frequency is a result of balancing changes of effective odour plume height (physical height + plume rise) and the width of the plume both in horizontal and vertical direction.

The average changes of odour concentrations were 18.4%, 16.3%, and 26.4% under unstable, neutral, and stable conditions when the stack diameter decreased from 3 m to 1.5 m. The odour frequencies increased 4.9%, 2.8% under unstable and neutral conditions when decreasing stack diameter. Most of the average elasticity values for odour concentration were between -0.5 and 0.5, which means that with the 1% changes of stack diameter, the changes of odour concentration were less than 0.5%. It can be concluded that LODM's sensitivity to stack diameter is medium for odour concentration. Most of the absolute elasticity values for the odour frequency were in the range of 0.01 to 0.1, thus the sensitivity of odour frequency to stack diameter is low.

Exit velocity Exit velocity is also an important parameter in determining plume rise. When exit velocity decreased, the plume rise decreased and the downwind odour concentration and frequency increased in most cases. From Figs. 6 and 7, and Table 4, the decrease of exit velocity had greater effect on odour concentration and odour frequency than the increase of it. For example, when exit velocity increased from 0.5 m s^{-1} to 0.75 m s^{-1} under unstable conditions, the average elasticity values for odour concentration and odour frequency were -0.27 and -0.08, while the corresponding values were 0.44 and 0.1, when the exit velocity decreased from 0.5 m s^{-1} to 0.25 m s^{-1}. From Table 4, we can also find that most of the absolute values of elasticity for odour concentration were less than 0.5, which showed that exit velocity had medium sensitivity to the LODM predicted odour concentration. For odour frequency, the model had low sensitivity to exit

Table 6. Sensitivity analysis of odour concentration and frequency to emission rate with a control value of 500,000 OU s^{-1}.

Stability	Change, %	Concentration				Frequency			
		Ave. C Change,%	S(0.5)	S(5)	S(ave)	Ave. F Change, %	S(0.5)	S(5)	S(ave)
Unstable	-50	-50.0	-1.00	-1.00	-1.00	-16.5	-0.24	-0.43	-0.34
	50	50.0	1.00	1.00	1.00	8.9	0.14	0.23	0.19
Neutral	-50	-50.0	-1.00	-1.00	-1.00	-13.1	-0.20	-0.33	-0.31
	50	50.0	1.00	1.00	1.00	7.1	0.12	0.18	0.18
Stable	-50	-50.0	-1.00	-1.00	-1.00	-11.0	-0.26	-0.27	-0.25
	50	50.0	1.00	1.00	1.00	6.0	0.16	0.14	0.14

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

Table 7. Sensitivity analysis of odour concentration and frequency to surface roughness with a control value of 0.1m.

Stability	Change		Concentration				Frequency			
	%	New	Ave. C	S(0.5)	S(5)	S(ave)	Ave. F	S(0.5)	S(5)	S(ave)
Unstable	-90	0.01	-2.6	-0.03	-0.06	-0.05	-1.3	-0.01	-0.02	-0.01
	400	0.5	22.7	0.05	0.04	0.04	2.9	0.00	0.01	0.01
	900	1	19.8	0.02	0.02	0.02	3.5	0.00	0.01	0.00
	1400	1.5	19.5	0.01	0.01	0.01	4.2	0.00	0.00	0.00
Neutral	-90	0.01	316.5	0.11	0.12	0.12	-1.7	0.00	0.01	0.02
	400	0.5	347.2	0.04	0.03	0.03	-0.9	0.01	0.01	0.01
	900	1	290.1	0.00	0.00	0.00	-3.3	0.00	0.00	0.00
	1400	1.5	249.5	-0.01	-0.01	-0.01	-5.3	0.00	0.00	0.00
Stable	-90	0.01	13.7	-	2.50	0.70	-87.5	-	-0.80	-0.84
	400	0.5	17.3	-	-0.05	-0.05	-39.5	-	0.04	0.05
	900	1	35.4	-	-0.04	-0.04	-39.3	-	0.02	0.02
	1400	1.5	24.4	-	-0.03	-0.03	-39.8	-	0.01	0.01

Ave. C Change, %: percentages of averaged changes of odour concentration; Ave. F Change, %: percentages of averaged changes of odour frequency; S(0.5): elasticity values calculated at downwind distances of 0.5 km; S(5): elasticity values calculated at downwind distances of 5 km.

velocity under unstable and neutral conditions, while it is indifferent under stable condition. It was surprising to see that the values (averaged change and elasticity) of model sensitivity to exit velocity under unstable and neutral conditions were same as those to stack diameter. Under the simulation conditions (ambient temperature: 20 °C, wind speed: 2.5 m/s, and exit temperature: 22 °C as shown in Table 1), the plume rise was determined by momentum rise instead of buoyant rise under unstable and neutral condition. Then the plume rise was calculated as the function of the product of stack diameter and exit velocity, which remained the same when changing stack diameter or exit velocity with 50% while keeping the other one constant.

Exit temperature Exit temperature is also one of the parameters in the model to determine the plume rise. From Figs. 8 and 9, and Table 5, under unstable and neutral conditions, the decrease of exit temperature from 22 to 20 °C had very slight effects on downwind concentration and frequency. When calculating plume rise, the difference between exit temperature and ambient temperature was used to determine whether the plume was momentum rise

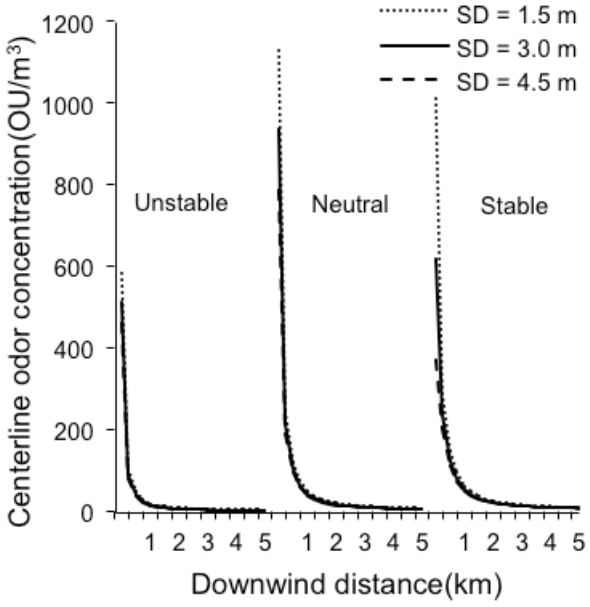

Fig. 4. Centerline odour concentrations for different stack diameters (SD).

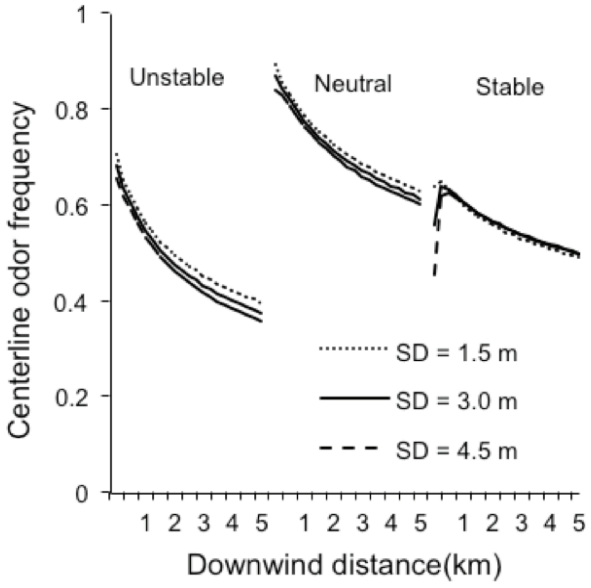

Fig. 5. Centerline odour frequencies for different stack diameters (SD).

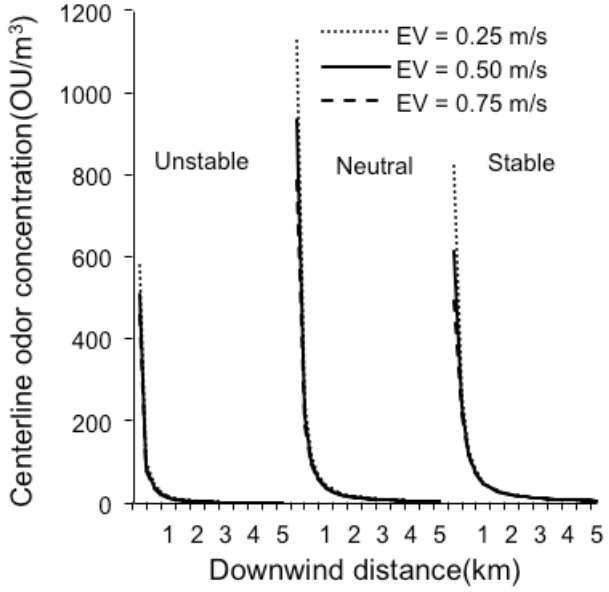

Fig. 6. Centerline odour concentrations for different exit velocities (EV).

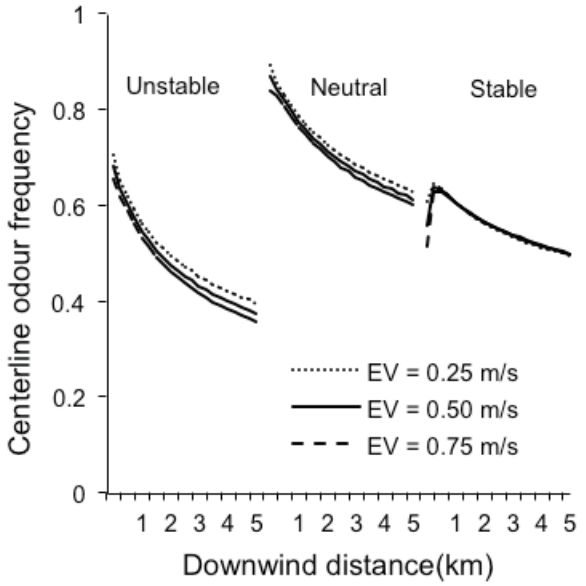

Fig. 7. Centerline odour frequencies for different exit velocities (EV).

or buoyant rise dominated. In current simulation, when the exit temperature was 22 or 20 °C, the plume rise was momentum rise dominated; the calculation of final plume rise was independent on the exit temperature. The slight difference resulted from the difference of distance that required for the plume to reach final plume rise. However, under unstable and neutral conditions, increase of the exit temperature by 2 °C would change the plume rise from momentum rise dominated to buoyant rise dominated resulting in decreases of the odour concentrations and frequencies. The average elasticity values are -0.44 and -0.29 for odour concentration and -0.12 and -0.09 for odour frequency when increasing exit temperature by 2 °C under unstable condition and neutral condition. Under stable condition, both increasing and decreasing exit temperatures caused changes in odour concentrations and odour frequencies. The average elasticity values are 2.36 for odour concentration and -0.68 for odour frequency when decreasing and increasing exit temperature by 2 °C. Overall, the sensitivity of LODM predicted odour concentration to exit temperature is high while its sensitivity of odour frequency is medium.

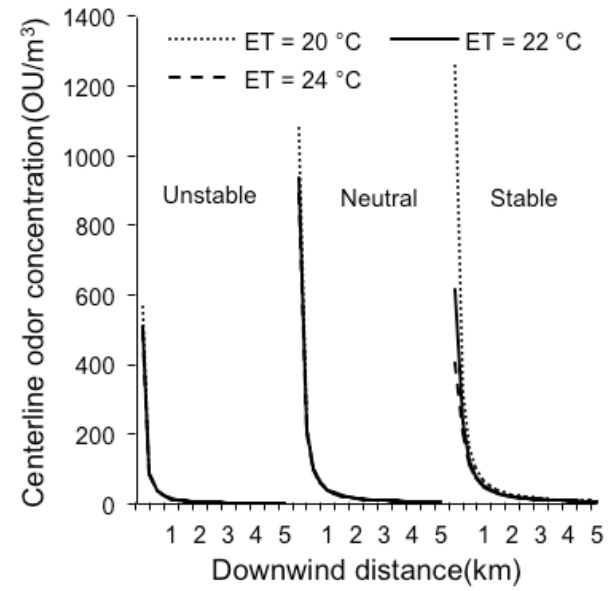

Fig. 8. Centerline odour concentrations for different exit temperatures (ET).

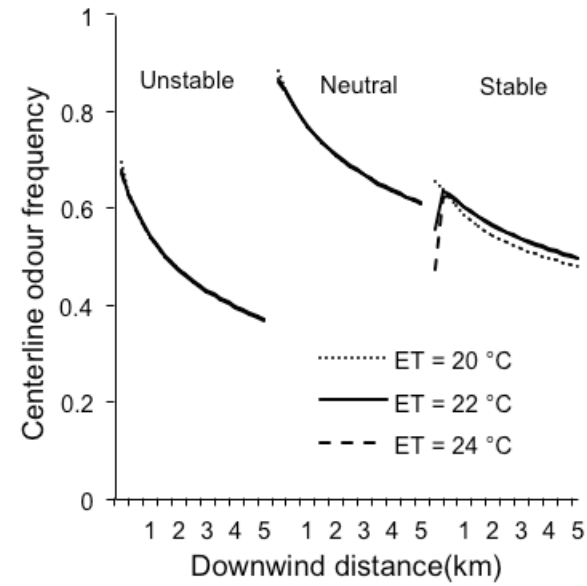

Fig. 9. Centerline odour frequencies for different exit temperatures (ET).

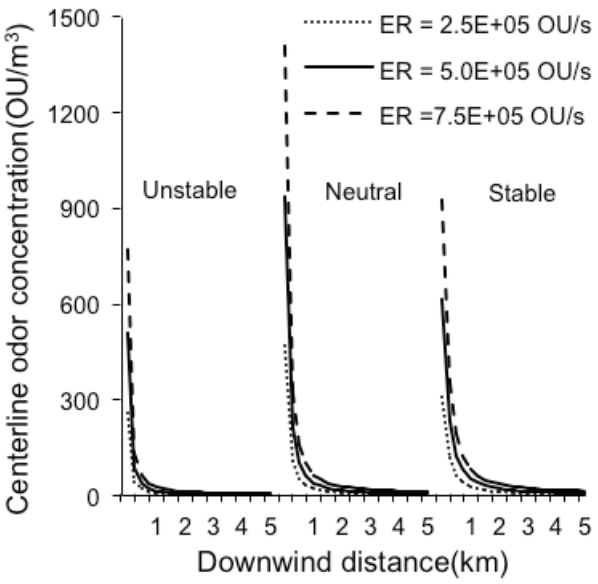

Fig. 10. Centerline odour Concentrations for different emission rates (ER).

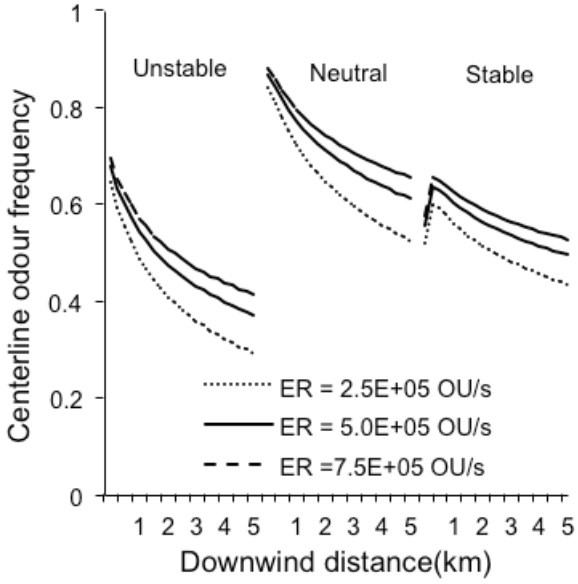

Fig. 11. Centerline odour frequencies for different emission rates (ER).

Emission rate The sensitivity of LODM to emission rate is shown in Figs. 10 and 11, and Table 6. The downwind mean odour concentration has a linear relationship with emission rate. Therefore, the model sensitivity of emission rate is high. However, the change of emission rate does not have the same effect on odour frequency. It is easy to explain considering the odour frequency used here is the odour frequency that odour concentration equals to or exceeds 1 OU m^{-3}. Then even if the emission rate decreases or increases by 50%, the frequency of the occurrence of odour concentrations equal to or exceeding 1 OU m^{-3} will not change at the same extent. For example, the hourly odour frequency of 1 OU m^{-3} at a receptor was 0.75, which meant that 75% of time in this hour the receptor would expose to odour $\geq$ 1 OU m^{-3}. When the emission rate decreased 50%, the hourly odour concentration and short time odour concentration would also decrease by 50%. However, only when the short time odour concentration decreased to below 1 OU m^{-3} the hourly frequency would decrease. The decrease of hourly frequency would be less than the extent of the decrease of odour concentration. When decreasing odour emission rate by 1%, the odour frequency decreased 0.34%, 0.31%, and 0.25% under unstable, neutral, and stable conditions, respectively. When increasing odour emission rate by 1%, the odour frequency increased 0.19%, 0.18%, and 0.14% under the three different stability conditions. Overall, the sensitivity of model predicted odour concentration to emission rate was high, while the sensitivity of odour frequency is medium.

Surface roughness, albedo, and Bowen ratio

The surface roughness length is related to the height of obstacles to wind flow, but also influenced by the shape, flexibility and density of vegetation (Smith 1993; USEPA 2004).Values range from less than 0.001 m over a calm water surface to 1 m or higher over a forest. Albedo is the ratio of reflective solar radiation by the surface to incident solar radiation. Typical values range from 0.1 for thick deciduous forests to 0.90 for fresh snow (USEPA 2004). Daytime Bowen ratio is a ratio of sensible heat flux to latent heat flux, which is an indicator of surface moisture. Midday values of Bowen ratio range from 0.1 over water to 10.0 over desert (USEPA 2004). Surface roughness plays an important role in both characterizing the atmosphere and determining the Hogstrŏm dispersion parameters in LODM. However, the model sensitivity to surface roughness under neutral and unstable conditions was low for odour concentration as most of the elasticity values are below 0.10 and indifferent for odour frequency. Under stable conditions, the effect of roughness was larger than those under unstable and neutral conditions as shown in Table 7. Especially, when roughness changes from 0.1 m to 0.01 m, the changes of odour concentration and frequency was 0.70 and -0.84, thus the sensitivity was high. Albedo and Bowen ratio are used to derive meteorological parameters at daytime. The model sensitivity to them was indifferent.

DISCUSSION

One of the important applications of the sensitivity analysis is to determine the importance of accuracy of the input parameters to the model. The elasticity values determine the change of model predicted odour concentration and odour frequency regarding each percent change of input parameters. From the sensitivity analysis result, emission rate is the most important input parameter that is linearly related to the model predicted odour concentration and has medium sensitivity to the odour frequency. For a building source, odor emission rate is the

product of the odor concentration of the exhaust air and ventilation rate of the building. The odour emission rate is very difficult to measure and presents great variations due to the uncertainty of odour concentration measurements, the complexity of exhaust for livestock buildings, and the temporal variation of odour emission rate. The odour concentration of the exhaust odour sample is usually measured by a dynamic triangular olfactometry method. An odour panel consisted of 5-8 odour assessors is applied to test the odour. The variances of the olfactometry can be found from a specific panel, within the panel, inter-panel, and inter-laboratory. The inter-laboratory variance can be as high as 0.30 of the threshold log values (Oxbol 2004). The internationally accepted European Olfactometry standard EN13725 (CEN 2003) provides details on quality assurance and quality control (QA/QC) requirements to be met by the odour-testing laboratory. By strictly following the standard, the olfactometry measured odour concentrations are considered acceptable input for odour dispersion models. For animal buildings, exhaust air is vented through openings in the walls and roofs of the building. There are often a number of vertical or horizontal openings or fans for one building. Due to the complex structures of the openings and fans of livestock building, it is very difficult to consider the flow rate of the odor emissions from livestock buildings. Odour emission rates change constantly with changing animal mass and number and with outside weather conditions. Usually, the means or geometric means of the limited measured odor emission rates for each type of odor sources were used as representative values in odor dispersion and setback modeling without considering the diurnal and seasonal variations (Zhu et al. 2000; Jacobson et al. 2000; Lim et al. 2000). However, large variations in annual and diurnal odor emission rates have been found (Guo et al. 2006; Wang 2007; Sun et al. 2008). It was suggested that multiple measurements should be taken from an odor source to obtain the mean, maximum, and minimum odor emission rates for air dispersion modeling purposes.

Another application of sensitivity analysis is to investigate the effect of the change of the controllable source parameters (stack height, diameter, exit velocity, exit temperature, and emission rate) regarding odour issues. When odour problems occur to existing livestock operations, a potential approach to control odour dispersion is to modify such parameters. For a livestock building or barn, the building exhausts air by openings and fans mounted on the wall or roof. It is unrealistic to modify the source physical characteristics (stack height and stack diameter). The temperature and the ventilation of animal buildings are determined by the environmental requirements of animals. Therefore, the only practical option would be to change emission rate.

CONCLUSION

The sensitivities of LODM to its input source and surface parameters were analyzed using averaged change of odour concentration and odour frequency and a defined elasticity. The three source parameters (stack height, stack diameter, and exit velocity) have the similar medium impact on concentrations and low impact on frequencies. Emission rate and exit temperature has high sensitivity for LODM predicted odour concentration and medium sensitivity to odour frequency. Among the three surface parameters, LODM has low sensitivity to surface roughness while its sensitivity to albedo and Bowen ratio is negligible.

ACKNOWLEDGEMENT

This research has been funded by the CIHR Strategic Training Program in Public Health and the Agricultural Rural Ecosystem (PHARE), the Canadian Centre for Health and Safety in Agriculture, and CIHR Partner Institutes including the Institute of Health Services and Policy Research, Institute of Circulatory and Respiratory Health, Institute of Infection and Immunity, and the Institute of Population and Public Health.

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