

IMPROVING THE LOW-WIND PERFORMANCE OF THE AERMOD ATMOSPHERIC DISPERSION MODEL FOR PREDICTING SHORT-RANGE IMPACTS OF LIVESTOCK AMMONIA EMISSIONS

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Abstract: Short-range impacts to sensitive ecosystems as a result of ammonia emitted by livestock farms are often assessed using atmospheric dispersion modelling systems such as AERMOD. These assessments evaluate mean annual atmospheric concentrations of ammonia and nitrogen deposition rates at the ecosystem location for comparison with ecosystem damage thresholds. However, predictions of mean annual atmospheric concentrations can be dominated by periods of stable night-time conditions, which can contribute significantly to mean concentrations. AERMOD has been demonstrated to overestimate concentrations in certain stable low-wind conditions and so the model could potentially overestimate the short-range impacts of livestock ammonia emissions. This paper tests several modifications to the parameterisation of AERMOD (v12345) that aim to improve model predictions in low-wind conditions. The modifications are first described and then are applied to three pig farm case studies in the USA, Denmark and Spain to assess whether the modifications improve long-term mean ammonia concentration predictions through improved model performance. For these three case studies, most of the modifications tested improved model performance as a result of reducing the long-term mean concentration predictions, with the largest effect for low- or ground-level sources (e.g. slurry lagoons or naturally ventilated housing).

Key words: Ammonia, Agriculture, AERMOD, Atmospheric Dispersion Modelling, Low wind speed

INTRODUCTION

Ammonia emitted into the atmosphere from agricultural sources can have an impact on nearby sensitive ecosystems, either through elevated ambient concentrations or dry/wet deposition to vegetation and soil surfaces. Short-range atmospheric dispersion models such as AERMOD are often used to assess these potential impacts on semi-natural ecosystems (Theobald *et al.*, 2012). Recent studies have shown how AERMOD can overestimate atmospheric concentrations under low-wind stable conditions. In order to correct this overestimation, Paine *et al.* (2010) suggested an empirical correction to the calculation of the friction velocity (u_*) for low-wind stable conditions based on a linear relationship between u_* and the wind speed. Paine *et al.* (2010) also suggested an increase in the minimum value of the crosswind turbulence (σ_v) from 0.2 to 0.4 m s⁻¹. More recently the developers of AERMOD have included BETA options in the model to improve low wind speed performance (US EPA, 2012). These options include the parameterisation of u_* proposed by Qian and Venkatram (2011):

$$u_* = \frac{C_{DN}^{1/2} U}{2} \frac{1 + \exp(-r^2/2)}{1 - \exp(-2/r)}, \quad (1)$$

where C_{DN} is the drag coefficient for neutral conditions, U is the wind speed and r is the ratio between the wind speed and a critical wind speed (U_{crit}). The AERMOD BETA options also include two additional low wind options: LOWWIND1 (Increased $\sigma_{v min}$ and with horizontal meander) and LOWWIND2 (Increased $\sigma_{v min}$ and no horizontal meander). This study applies these suggested modifications and BETA options to assess whether they improve predicted concentrations for three agricultural case studies.

MATERIALS AND METHODS

The AERMOD parameterisations applied are summarised in Table 1.

Table 1. Parameterisations tested

Scenario	u^* parameterisation	Dispersion parameterisation	Reference
Base	Original	Original	Cimorelli <i>et al.</i> (2002)
P1	Linear with wind speed	Original	Paine <i>et al.</i> (2010)
P2	Original	Increased $\sigma_{v\ min}$	
P3	Linear with wind speed	Increased $\sigma_{v\ min}$	
BETA 0	Equation (1)	Original	Qian and Venkatram (2011)
BETA 1	Equation (1)	Increased $\sigma_{v\ min}$, no horizontal meander	US EPA (2012)
BETA 2	Equation (1)	Increased $\sigma_{v\ min}$, horizontal meander	

Mean atmospheric ammonia concentrations were simulated and compared with measured values for three case study pig farms (Table 2). Two of these case studies (Falster and North Carolina) were used by Theobald *et al.* (2012) to evaluate the performance of several atmospheric dispersion models. A third case study pig farm (Aguilafuente) was added for this study in order to assess model performance for Mediterranean climatic conditions.

Table 2. Case studies used

Case study	Location	Source information	Study length	Reference
Aguilafuente	Segovia, Spain	Three mechanically ventilated pig houses and a slurry lagoon	1 year	None
Falster	Denmark	One mechanically ventilated pig house	3 months	Pedersen <i>et al.</i> (2007)
North Carolina	USA	Five naturally ventilated pig houses and a slurry lagoon	1 year	Walker <i>et al.</i> (2008)

Long-term mean ammonia concentrations were simulated and compared with those measured using passive samplers located at various distances and directions from the sources. Long-term mean concentrations were used for this study since they are used in ecological impact assessments in Europe (e.g. for the UK see Environment Agency (2010)). Model performance was assessed using the performance indicators suggested by Chang and Hanna (2004): fractional bias (*FB*); geometric mean bias (*MG*); normalised mean square error (*NMSE*); geometric variance (*VG*); the number of predictions within a factor of two of the observed values (*FAC2*) and the correlation coefficient (*R* or R^2).

RESULTS

Effect of modifications on mean concentrations

The modifications to the AERMOD model generally decreased long-term mean concentration predictions for all three case studies (Figure 1). The largest effect was for the North Carolina case study (volume and area sources), for which all of the modifications except P2 (increased $\sigma_{v\ min}$) decreased long-term mean concentrations by 28-57%. The overall effect of the modifications for the Aguilafuente case study (point and area sources) was similar but smaller, although increases in concentrations were also predicted for some measurement locations. The smallest effect of the modifications was for the Falster case study (point sources) for which the concentration predictions varied by -21% to +9%. The two modifications based on a linear relationship of u^* with wind speed for low-wind stable conditions (P1 and P3) had a similar effect on mean concentrations although increasing $\sigma_{v\ min}$ (P3) increased the concentration predictions for some wind sectors for the Aguilafuente case study. Increasing $\sigma_{v\ min}$ on its own (P2) resulted in small overall changes in concentration predictions but substantial increases and decreases in the concentration predictions for individual locations. All three BETA modifications had a similar effect on long-term mean concentration predictions although BETA 1 (adjusted u^* , increased $\sigma_{v\ min}$,

no horizontal meander) was the only BETA modification that decreased overall concentration predictions for all three case studies.

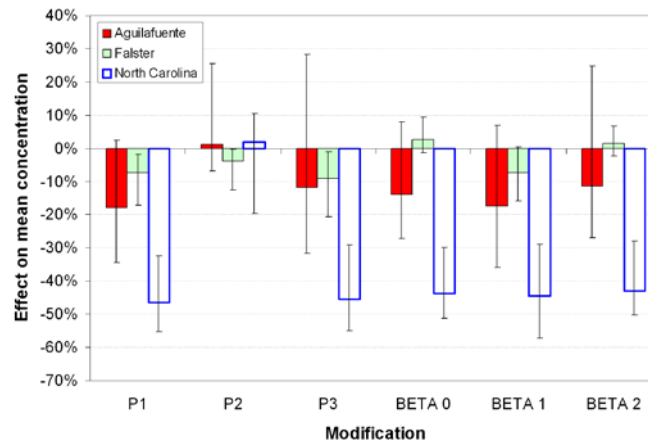


Figure 1. Effect of the modifications on long-term mean concentrations relative to the base case study, averaged over all measurement locations. Error bars show the range of the effect on the long-term mean concentrations for all measurement locations.

Effect of modifications on performance indicators

For the Aguilafuente case study, all modifications tested improved the indicator values of *FB* and *NMSE* (i.e. the points on Figure 2 are all closer to the origin than that of the base case study (0)). The indicator values of *MG* are all slightly worse than the base case study, although *MG* of the base case study (-0.004) was very close to the optimum. Improvements in the indicator values of *VG* were obtained with all modifications tested, except BETA 1. Values of *FAC2* were improved or left unchanged for all modifications whilst the linear correlation of the predicted concentrations with the measured values (R^2) was improved (not shown). For the Falster case study the effect of the modifications was to improve some of the indicator values whilst worsening others (Figure 3). The modifications P1-P3 and BETA 1 improved the values of *FAC2* and R^2 , whilst BETA 0 and BETA 2 worsened them. All performance indicator values were improved when the modifications were applied to the North Carolina case study, except for the P2 modification (increased $\sigma_{v \text{ min}}$ only) (Figure 4), which worsened all indicator values except *FAC2* (not shown). Overall the modifications have varying effects on the performance indicator values depending on the case study. This variability is probably due to the combined effects of source types, source to measurement location distances and meteorological conditions. Overall the modifications result in an improvement of the indicator values (with a few exceptions) although the changes are not large. In fact the modifications result in few changes to model acceptability based on the acceptability criteria of Chang and Hanna (2004), with the exception of the Carolina case study, for which the modifications result in the model meeting the bias acceptability criteria (*FB* and *MG*) as well as the *FAC2* criterion due to the decrease in prediction concentrations.

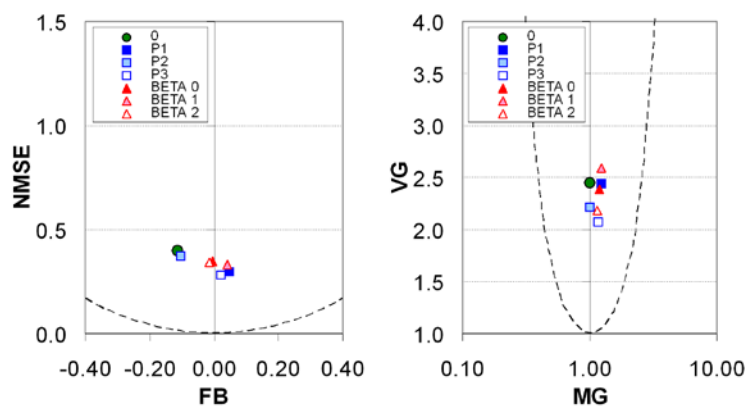


Figure 2. Plotted values of the performance indicators: fractional bias (*FB*); geometric mean bias (*MG*); normalised mean square error (*NMSE*) and geometric variance (*VG*) for the **Aguilafuente** case study. Dotted lines indicate the theoretical minimum values for *NMSE* and *VG*.

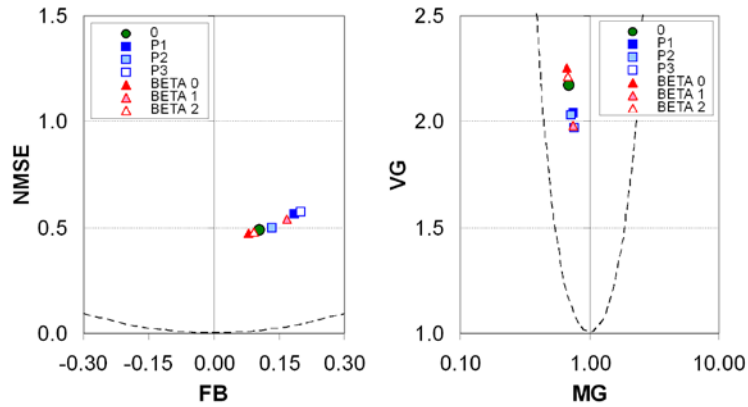


Figure 3. Plotted values of the performance indicators: fractional bias (*FB*); geometric mean bias (*MG*); normalised mean square error (*NMSE*) and geometric variance (*VG*) for the **Falster** case study. Dotted lines indicate the theoretical minimum values for *NMSE* and *VG*.

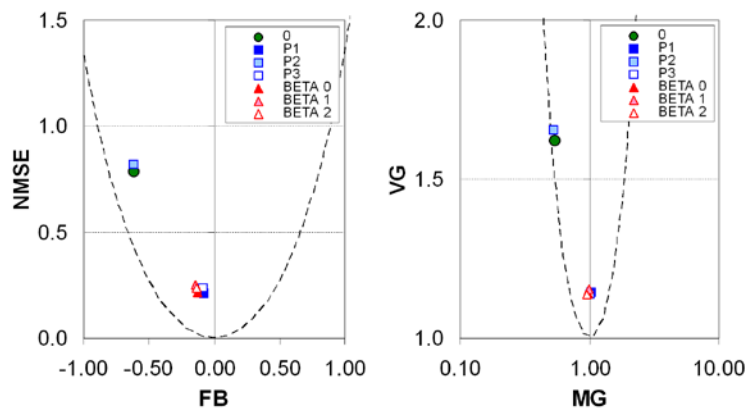


Figure 4. Plotted values of the performance indicators: fractional bias (*FB*); geometric mean bias (*MG*); normalised mean square error (*NMSE*) and geometric variance (*VG*) for the **North Carolina** case study. Dotted lines indicate the theoretical minimum values for *NMSE* and *VG*.

DISCUSSION AND CONCLUSIONS

This study tests several modifications to the AERMOD model aimed to improved the low-wind speed performance of the model for situations similar to those encountered in environmental impact assessments for ammonia emissions from agricultural practices (i.e. prediction of long-term mean concentrations). As the above analysis shows, the modifications improved model performance for most cases, as demonstrated by the fact that more performance indicator values were improved as a result of the modifications than were worsened. The smallest improvement was obtained using modification P2 (increased $\sigma_{v \text{ min}}$ only). This modification increased lateral dispersion of the plume, decreasing concentrations in the main wind directions and increasing concentrations in the less frequent wind directions. This resulted in little or no improvement in model performance (see Figures 2-4). For these three case studies, the largest improvement in model performance was obtained based on a linear relationship of u_* with wind speed for low-wind stable conditions (P1 and P3), although the BETA modifications gave similar improvements in some cases. The improvements in model performance varied depending on the case study. Part of this variation depended on the source and measurement location characteristics. Concentration predictions were least affected at measurement locations close to elevated point sources, whereas they were most affected close to area and volume sources. To illustrate these differences, Figure 5 shows the hourly concentration predictions as a result of the emissions from different source types plotted against wind speed when the modifications P1-3 are applied to the Aguilafuente case study. Predicted concentrations as a result of the housing emissions (elevated point sources) are affected less by the modifications than those resulting from the slurry lagoon emissions (area source). This shows that the dispersion from ground-level area sources is more sensitive to the modifications to u_* than that from elevated point sources, which would explain why the modifications had a small effect on the predicted mean concentrations for the

Falster case study (elevated point sources). This would also explain the large effect of the modifications on the concentration predictions for the North Carolina case study since all emission sources are ground- or low-level.

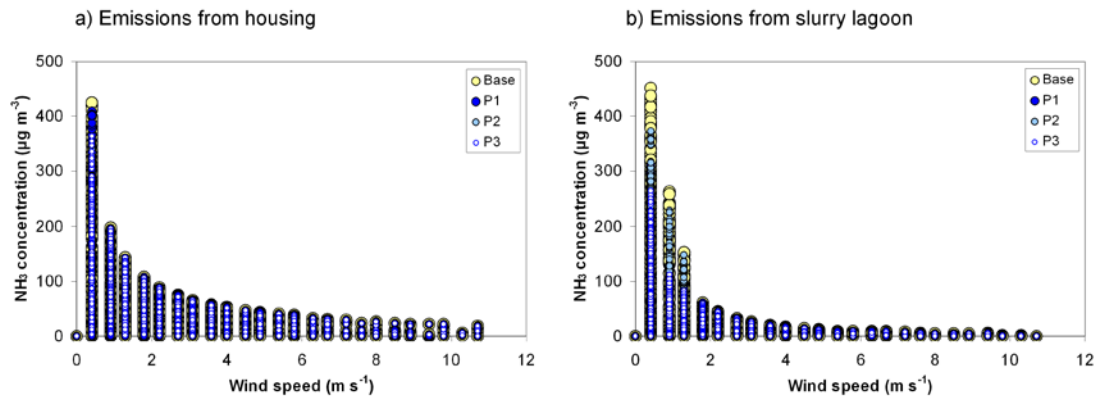


Figure 5. Hourly concentration predictions as a result of the emissions from a) animal houses and b) slurry lagoon plotted against wind speed for the original model parameterisation (Base) and when the modifications P1-3 are applied to the AguilaFuente case study.

The focus of this work has been on long-term mean concentration predictions since these are the focus for environmental impact assessments for ammonia. However, it is useful also to look at how these modifications affect hourly percentile concentrations to make this study relevant to work on other regulatory pollutants (e.g. nitrogen dioxide, particulate matter etc.). Similarly to the effect on long-term mean concentrations, the modifications affect the percentile concentrations least for the Falster case study (98th percentile concentrations decreased by 1-7%) and most for the North Carolina case study. For the latter study the P2 modification (increased $\sigma_{v, min}$ only) decreased 98th percentile concentrations by just 3% whereas the other modifications decreased them by 18-58%.

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