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Suitability and uncertainty of two models for the simulation of ammonia dispersion from a pig farm located in an area with frequent calm conditions

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HIGHLIGHTS

- Two dispersion models are compared for a site with frequent calm conditions.
- Modelled ammonia concentrations around a pig farm are compared with measurements.
- Model uncertainty due to input uncertainty is approximately a factor of 2.
- The largest contribution to prediction uncertainty is uncertainty in emission rates.
- Differences in model performance are mainly due to periods with low wind speeds.

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ABSTRACT

We used two atmospheric dispersion models (ADMS and AERMOD) to simulate the short-range dispersion of ammonia emitted by two pig farms to assess their suitability in situations with frequent calm meteorological conditions. Simulations were carried out both using constant and temporally-varying emission rates to evaluate the effect on the model predictions. Monthly and annual mean concentrations predicted by the models at locations within one kilometre of the farms were compared with measured values. AERMOD predicted higher concentrations than ADMS (by a factor of 6–7, on average) and predicted the atmospheric concentrations more accurately for both the monthly and annual simulations. The differences between the concentrations predicted by the two models were mainly the result of different calm wind speed thresholds used by the models. The use of temporally-varying emission rates improved the performance of both models for the monthly and annual simulations with respect to the constant emission simulations. A Monte Carlo uncertainty analysis based on the inputs judged to be the most uncertain for the selected case study estimated a prediction uncertainty of ± a factor of two for both models with most of this due to uncertainty in emission rates.

1. Introduction

Ammonia (NH_3) 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 (Bobbink et al., 1998). Evidence of impacts of elevated NH_3 concentrations on vegetation has made it possible to define 'critical levels' for NH_3 exposure. An annual critical level of 3 $\mu g\ m^{-3}$ (with an uncertainty range of 2–4 $\mu g\ m^{-3}$) has been recommended for ecosystems containing higher plants only and a lower critical level of 1 $\mu g\ m^{-3}$ for ecosystems containing lichens or bryophytes (Cape et al., 2009). Based on current evidence, impacts to these ecosystems may occur when the annual mean NH_3 concentration is above the critical level. Similarly, impact thresholds of long-term (e.g. 20–30 years) nitrogen deposition rates (critical loads) have also been developed for different ecosystem types (Achermann and Bobbink, 2003).

In Europe, where NH_3 is a regulated pollutant, potential impacts of agricultural emissions to nearby sensitive habitats are normally assessed using atmospheric dispersion models. Model predictions

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of annual mean atmospheric NH_3 concentrations and nitrogen deposition rates are used to determine whether the critical levels and critical loads, respectively, of nearby sensitive habitats are likely to be exceeded. Since dry deposition rates are calculated by the models from ground-level concentrations using empirically-derived and uncertain deposition parameterisations, the deposition predictions are likely to be more uncertain than the concentration predictions (Environment Agency, 2010). For this reason, it may be preferable to base an environmental impact assessment on critical levels instead of critical loads. A range of different models are used for these assessments, with the choice of model depending on local expertise and model development programmes (Theobald et al., 2012). For example, in the United Kingdom, assessments are usually carried out using one of two advanced Gaussian dispersion models (Environment Agency, 2010): the Atmospheric Dispersion Modelling System (ADMS, Carruthers et al., 1994) or the AMS/EPA Regulatory Model (AERMOD, Cimorelli et al., 2002). These two models have been evaluated for a range of applications, including some agricultural case studies (Hill et al., 2001; Theobald et al., 2012) and, in general, perform acceptably when all model inputs (emissions rates, meteorological variables etc.) are known with sufficient accuracy.

However, for environmental impact assessments, assumptions and approximations have to be made when model inputs are not known accurately. For example, for assessments of environmental impacts of livestock facilities, emission rates are often assumed to be constant and based on national or international emission factors for each livestock type. Furthermore, meteorological data are normally taken from the nearest ‘representative’ meteorological station, which can be many kilometres from the assessment site. In addition, it may be difficult to obtain complete meteorological records due to sensor downtime or calm periods. Advanced Gaussian dispersion models such as AERMOD and ADMS include routines to simulate periods with low wind speeds. AERMOD, for example, uses a combined solution of a coherent plume (traditional Gaussian shape) and a radially-symmetric plume to simulate dispersion for low wind speeds. The model interpolates between these two plumes, tending to the radially-symmetric plume at very low wind speeds (US EPA, 2003). A similar approach is also used in ADMS, when the non-default calms option is selected (CERC, 2007). However, the default versions of the models cannot simulate ‘calm’ periods when the wind speed in the meteorological data record is zero and so these periods are removed from the model calculations. These are periods when the actual wind speed is less than the anemometer stalling speed but not necessarily zero. This is problematic because high concentrations may occur during these periods as a result of low dispersion rates. This problem is more commonly encountered when routine meteorological data from network stations are used (often the case for impact assessments), which tend to use cup anemometers, compared with meteorological data from research-grade model evaluation studies that use more advanced measurement techniques (e.g. ultrasonic anemometers). AERMOD identifies a calm period when the wind speed is below a user-defined threshold based on anemometer stalling speeds whereas ADMS has a default wind speed threshold of $0.75\ m\ s^{-1}$ at a height of 10 m when the calms option is not selected.

UK modelling guidance (Defra, 2009) recommends that models can be used for predicting annual mean concentrations when valid non-calm meteorological data are available for more than 75% of the modelling period (provided that there are no gaps of several weeks). However, it may not be possible to meet this criterion in locations with frequent calm periods and so there is a need to evaluate model performance when this criterion cannot be met.

As mentioned above, one of the assumptions frequently made in these assessments is that the emission rates are constant. However, emission rates of agricultural sources are not constant since they depend on many factors as a result of management practices and environmental conditions. The assumption of constant emissions may, therefore, affect the annual mean concentrations predicted by the models, although this has not been tested.

In this paper we simulate the atmospheric dispersion of NH_3 emitted by a Spanish pig farm with two advanced Gaussian dispersion models: ADMS and AERMOD. This case study was chosen because the pig farm is located in a region with frequent calm winds and so is a good candidate to test the suitability of these two models for these meteorological conditions. This is done by statistically comparing monthly and annual mean NH_3 concentrations predicted by the models with those measured at multiple locations up to one km from the farm. Many of the model inputs are uncertain (emission rates, exit velocities, meteorological variables, etc.), as in many real impact assessments and so an uncertainty analysis has been done to assess the influence of these uncertainties on the models' predictions. We also test an emission model that better represents the temporal variability of the pig farm emissions. The objectives of this study were, therefore:

1. To assess the suitability of the two dispersion models ADMS and AERMOD for an agricultural case study with frequent low-wind conditions;
2. To quantify the uncertainty of model predictions due to uncertainties in input data;
3. To assess the effect on the concentration predictions of using an emissions model to simulate the hourly variability of emissions.

2. Materials and methods

2.1. Experimental site

A one year field experiment was carried out in the vicinity of a pig farm (Farm 1 in Fig. 1) in the region of Segovia, central Spain. The farm is a pig breeding unit with a fairly constant number of sows (565 animals, on average) with piglets up to 20 kg (1092 animals). The unit consists of three main buildings: the adaptation building for new sows (105 animals) (A in Fig. 1), the gestation building (370 animals) (B) and the birthing building (90 sows and 1092 piglets) (C). The buildings have fully-slatted floors with slurry pumped frequently to an outdoor lagoon (D). Slurry is removed periodically for application to nearby arable fields, although no information is available on where and when the slurry is applied. All buildings of the farm are mechanically ventilated with wall inlets. The adaptation building has four wall ventilation outlets, whilst the gestation and birthing buildings have roof outlets (Fig. 1). Approximately 1.2 km NW of the unit is another similar unit (Farm 2) with an average of 240 breeding sows in three buildings and an outdoor slurry lagoon. All buildings of this farm have roof ventilation outlets. The area is very flat and the land use around the two farms is arable fields (cereals and sunflowers) with some set-aside and woodland. Detailed management data for the arable fields (e.g. crops grown and fertiliser applications) are not available. There is also a small infrequently used road that passes through the experimental area.

2.2. Ammonia emission estimates

Ammonia emission data are not available for Farm 1 or Farm 2 and, therefore, emission estimates were taken from the emission inventory guidebook produced jointly by the European Monitoring and Evaluation Programme (EMEP) and the European Environment Agency (EEA) (EEA, 2009). The emissions were calculated using the