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Development of a fluctuating plume model for odour dispersion around buildings

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HIGHLIGHTS

- An FPM is developed to predict mean concentrations and fluctuations around obstacles.
- The model is validated using wind tunnel and field experimental data.
- The model provides very good concentration predictions downwind of the near-wake.
- In the near-wake the FPM underpredicts concentrations in relation to experimental data.
- The FPM predicts a more intermittent presence of gas in the near-wake.

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ABSTRACT

This paper presents a fluctuating plume model, which incorporates the PRIME algorithm in order to include the effect of plume elevation and downwash due to buoyancy and the presence of obstacles. The Gaussian fluctuating plume model has the ability to predict both mean concentrations and concentration fluctuations. Therefore, it is useful for modelling dispersion in cases where concentration fluctuations are important for environmental impact assessment, such as for odorous compounds. The model is validated using two different experimental datasets, one involving dispersion around a complex building in a wind tunnel and the other involving dispersion around an isolated cube in the field. The results suggest that the model in general predicts adequately mean concentrations and concentration fluctuation statistics, such as concentration peaks and intermittency, downwind of the near-wake. However, mainly due to the formulation of the PRIME algorithm, it underestimates concentrations in the near-wake recirculation region of the obstacle and although it can adequately predict the maximum intermittency value, it does not predict accurately its location. In general, the model appears to over-predict dispersion if compared to the wind tunnel data. This can be partly attributed to the larger scales of turbulence not reproduced in the wind tunnel as also suggested from the comparison of the model results with field data. Finally, due to the assumptions incorporated in PRIME, the model cannot capture the effect of the complex shape of a building on near-field dispersion.

1. Introduction

Due to the interest in dispersion in urban areas as well as near industrial and storage installations, a considerable amount of work has been carried out concerning dispersion around buildings, using either field and wind tunnel experiments or analytical and numerical modelling techniques (e.g. Aubrun and Leitl, 2004; Blocken et al., 2013; Mavroidis et al., 2003; Tominaga and Stathopoulos, 2009; De Melo et al., 2012). A tool developed specifically to include the effects of an obstacle on dispersion in Gaussian-based models is PRIME (Plume Rise Model Enhancement), which was developed by Schulman et al. (2000). This model incorporates the effect of plume elevation and downwash due to buoyancy and the presence of obstacles by enhancing the plume dispersion coefficients and accounting for the streamline deflection effect on plume rise. PRIME is included in analytical models commonly recommended by environmental agencies for urban and

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rural regions, such as AERMOD (Lee et al., 1996; Cimoreli et al., 2005) and CALPUFF (Scire et al., 2000).

The majority of atmospheric pollutant dispersion studies have been concerned with the examination of mean concentrations over a given time, typically hours in length. However, concentration fluctuation statistics are very important for estimating the potential hazards from pollutant releases in the atmosphere, for example in the case of flammability, toxicity and malodour nuisance. Such releases are very often occurring in the vicinity of industrial installations and other structures or within urban areas. Malodour nuisance is a problem occurring in built-up areas, causing several problems to the general public, ranging from annoyance, to headaches, insomnia, nausea, vomiting and irritation to the skin, nasal system and to the eyes (Schiffman and Williams, 2005). Dispersion models which account for the presence of odour sources can vary from simple Gaussian models to complex numerical models. Few Gaussian models have included parameters for the assessment of odour impact, such as peak concentration (maximum averaged concentration over periods shorter than 1 h) and frequency of occurrence of peak concentrations during a time interval (De Melo Lisboa et al., 2006; Schauberger et al., 2000).

The Fluctuating Plume Model (FPM), originally proposed by Gifford (1959) and developed by Murray et al. (1978), is an analytical model capable of providing the percentage of time during which concentration remains above or below a defined threshold. This characteristic turns the FPM a valuable tool for odorant compound dispersion modelling. Mussio et al. (2001) evaluated the performance of FPM and obtained better results for maximum odour concentrations than a Gaussian model adapted to account for odour perception average time by a constant factor. De Melo Lisboa et al. (2006) modelled odour dispersion using the FPM and obtained good agreement with field data. Vrieling and Nieuwstadt (2003) developed an FPM model to study dispersion from nearby line sources within a channel, based on DNS simulation results and Yee et al. (2003) studied the problem of interference of two plumes originating from nearby point sources using an FPM. In both these studies, FPM agreed qualitatively with experimental data. The use of FPM with different formulations to include the effects of the presence of a complex geometry obstacle on dispersion was investigated by Dourado (2007), who suggested that the formulations proposed by Gifford (1960), Gifford (1968), Turner (1969), Huber and Snyder (1976), Johnson et al. (1975) and Scire et al. (2000) did not adequately reproduce wind tunnel results. Recently, Yu et al. (2011a, 2011b) employed an FPM in order to estimate concentration of odorant gases emitted by a livestock building. The building effects were included using the method suggested by Turner (1969) and the model results showed higher agreement with field data at longer distances than at close range.

The present work describes the development of a Gaussian fluctuating plume model which is used to investigate odour dispersion modelling in the presence of obstacles, under neutral atmospheric stability conditions. To achieve this goal, the PRIME algorithm is incorporated in the FPM model. The FPM-PRIME model includes the effect of the presence of obstacles and allows for the prediction of concentration fluctuation statistics, such as peak concentrations and intermittency. The model is validated using two different experimental datasets: one involving wind tunnel (WT) measurements around a complex building and the other involving field measurements around a cubical building. While on one hand field experiments incorporate all the levels of turbulent scales and represent atmospheric dispersion of a fluctuating plume better than wind tunnel trials, on the other hand field campaigns are difficult and expensive. On the same time, the unsteadiness of the meteorological conditions makes their results very often non-representative of the statistical characteristics of the phenomena. Model evaluation studies are important to improve analytical models and to ensure the accuracy and reliability of pollutant dispersion simulations provided by them.

2. Materials and methods

2.1. Description OF the fluctuating plume model

The FPM was proposed by Gifford (1959), as a derivative of the traditional steady state Gaussian plume model in which the vertical and horizontal levels of concentration of an emitted pollutant downwind of the source followed a Gaussian distribution; but in the FPM, the plume fluctuates as a result of wind meandering and velocity fluctuation. The plume centreline position as well as concentration inside the plume follows a Gaussian distribution so that the long-term dispersion parameter of the Gaussian model and the FPM dispersion parameters are related by Equation (1).

$$\sigma_c^2 = \sigma^2 + \sigma_p^2 \tag{1}$$

where σ is the long-term dispersion parameter obtained from Briggs equations (Hanna et al., 1982) based on the atmospheric stability conditions, σ_c is the standard deviation of the plume centreline positions and σ_p is the plume segment dispersion parameter. The horizontal and vertical parameters (σ_{yp} and σ_{zp}) are calculated following Hoögstrom (1972). Both σ and σ_p depend on atmospheric stability and are a function of the distance from the source. The long term dispersion parameter value is higher than the plume segment dispersion parameter; thus, σ_c has the same order of magnitude with σ. Based on the dispersion coefficients, the FPM randomly generates a series of instantaneous plume positions that result in a series of concentrations for each receptor. These concentration series allow the determination of some useful parameters for odour impact assessment, such as intermittency, peak-to-mean concentration ratio and the 98th percentile concentration (Drew et al., 2007).

Intermittency is defined in this paper in two different ways. For the purposes of comparing the model results with the wind tunnel data (Section 3.1), it is defined as the percentage of time during which the instantaneous concentration is higher than 0.25% of the concentration at the source (Aubrun and Leitl, 2004). On the other hand, in order to compare the model results with the field experiments (Section 3.2), it is defined as the percentage of time during which the instantaneous concentration is lower than the detection limit (Mavroidis et al., 2003). The peak-to-mean concentration ratio (P/M) is obtained by dividing the highest concentration in the concentration series to its average value. The 98th percentile concentration is calculated as the concentration which is exceeded during 2% of the time and is also a useful indicator of peak concentrations.

2.2. Incorporation of the PRIME algorithm in the FPM

The Plume Rise Model Enhancements (PRIME) algorithm (Schulman et al., 2000) was proposed for assessing the effects of obstacles on the velocity field and consecutively on pollutant dispersion. It was first included in the ISC3 regulatory model and is currently used in the AERMOD and CALPUFF regulatory models. The model includes the effect of the obstacle on the streamlines slopes which causes plume elevation and/or downwash that may allow for the plume to be capture by the obstacle wake. It is used to determine the plume trajectory in the modified flow field. Concentration calculation takes into account the effect of the fraction of plume captured by the obstacle cavity, which is re-emitted to the obstacle far wake. The different regions of the building wake are described in detail by Schulman et al. (2000).